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Value chain and production cost optimization by integrating additive manufacturing in injection molding process chain

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Abstract

Additive manufacturing (AM) can create considerable value when integrated into conventional manufacturing process chains. Tooling for new molded product development as pilot case of integration of AM in the injection molding process chain is investigated. The study shows that injection molding based on AM for fabrication of polymer tool inserts is economically advantageous allowing 80–90% production costs reduction as compared with a conventional tooling process chain based on machining. Fabrication of soft tools with AM results in a production lead time reduction in the range of 60–70% compared to the time required to machine mold inserts in brass or aluminum.

Keywords Additive manufacturing · Injection molding · Tooling · Production cost

1 Introduction

Additive manufacturing (AM) refers to a series of processes that have in common the use of a 3D CAD design to manufacture an object layer-by-layer. The origin of AM dates back to 1986 when it first introduced the process of stereolithography (SL) or stereolithography apparatus (SLA) commercialized by 3D systems for prototyping purposes.

To distinguish the use of layer-based manufacturing technologies between their use for prototyping and end-use production, the ASTM International committee F2792 defined AM as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1].

AM technologies have been characterized by an impressive double-digit growth, with a compound annual growth rate (CAGR) over the past 27 years of 26.2% [2]. A large market

for AM has been created in the past 20 years and a higher industrial adoption is foreseen. The market growth and the increasing use of AM have created a surrounding hype around the technology of being able to replace conventional manufacturing process.

This research's aim is to present how synergies between AM and conventional manufacturing processes can be achieved and as a consequence how it is possible to foster the adoption of AM in support of existing process chains for volume production.

In this work, the focus will be on identifying how AM is able to add value if adopted to support the manufacturing process of injection molding. Injection molding is the most important process used to manufacture plastic products. Today, injection molding is used to process more than one third of all thermoplastic materials worldwide, and more than half of all polymer processing equipment is for injection molding. The injection molding process is highly suitable for the mass manufacturing of plastic products characterized by complex shapes and dimensional tolerances down to 0.1 to 1% of the component's dimension. The components of an injection molding machine are the plasticising unit (where thermoplastic material is melted), clamping unit (to secure the closure of the mold halves to form a stably closed mold cavity), and the mold. An injection molding cycle begins with the mold closure, followed by the injection of the polymer into the mold cavity by the reciprocating screw. While the cavity is

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filling the molten material starts to solidify and when the part is sufficiently cool, the mold opens and the part is ejected [3].

Following the increasing technological development of AM, its use for fabrication of mold inserts is increasingly becoming an industrially viable solution. Recent research has shown the potentials of integrating AM for production of plastic molds inserts in terms of technological, operational, and environmental benefits [4–7].

As far as plastic parts manufacturing, cost models on AM have been built so far solely on the assumption that AM could substitute injection molding for accurate end-use parts production [8–13]. However, an analysis of the competitive and economic advantages of integrating AM into an injection molding process chains by manufacturing the tool cavity in which the polymer melt is subsequently injected has not been performed so far. In response to this literature gap, this research addresses the advantages of additive manufacturing utilized in a synergistic rather than disruptive way to create additional value in the injection molding process chain. When trying to use additive manufacturing to compete with the productivity of injection molding by directly manufacture each component (i.e., AM as replacement of IM), this leads very quickly to an extremely high production cost for the AM technology for the manufacturing of just few parts, which is clearly not competitive (see point A in Fig. 1). Instead, we envisage an integrated AM and IM process chain, in which AM is used to produce part of the injection molding tool creating the conditions for a more cost effective production. In this scenario, the production volume which is economically viable is from the hundreds of components up to the single digit thousands of parts (see point B in Fig. 1). After this production volume, there will be the transition of AM as support of IM towards a full injection molding high volume production (see Fig. 1).

2 AM technology and additive manufactured part

Digital light processing (DLP) is one of the most accurate AM technologies available on the market [14, 15]. A DLP machine is characterized by a vat filled with a photopolymer liquid resin and a horizontal platform that moves vertically on which the part is attached and lifted horizontally from the bottom to the top from the vat. A digital light projector, projects the object geometry layer-by-layer in the resin vat, which absorbs the light and solidify the material following a photopolymerization process. AM on a DLP machine involves the following main steps:

(1) Pre-processing that includes setting the building environment by determining and choosing the appropriate material, layer thickness, and build style
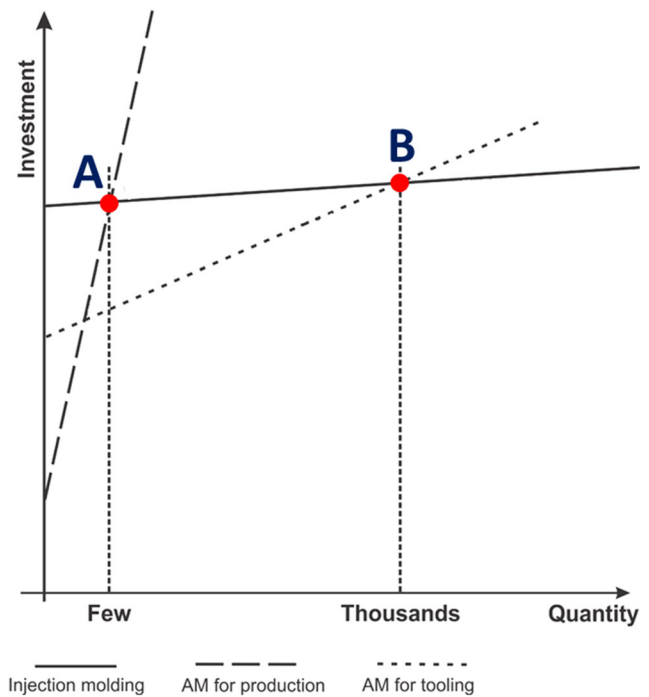
Fig. 1 Cost curves of AM as injection molding replacement or support technology for tooling

(2) Verify the correctness of the STL file and resolution of any errors

(3) Setting the appropriate part orientation in the build platform by considering the trade-off between surface quality and building speed

(4) Generation of necessary support structures for the part

(5) Production step and specifically a top-down layer-by-layer manufacturing process

(6) Post-processing that includes (a) cleaning the part from liquid resin; (b) removing support material and drying the part; (c) post-curing the part into a UV light oven; (d) sanding, grinding, or machining to achieve the desired surface finish

The part considered in this study is a mold insert equipped with micro features discussed in [6] to fit a four cavity mold and fabricated by the DLP AM technology. In particular, the DLP AM technology is here used for a soft tooling purpose, that is to make tools and tool inserts from prototype materials, for example, from stereolithography resin. Prototype tooling is therefore characterized by quickly and easily made low-volume tools [16]. A drawing of the soft tooling insert in Fig. 2a. In the injection molding machine (see Fig. 2b) is mounted the mold (see Fig. 2c), where the additive manufactured inserts are assembled (see Fig. 2d) and subsequently employed for the injection molding pilot production. In Fig. 2e, an example of the injection molded component (left) produced using the additive manufactured tool insert
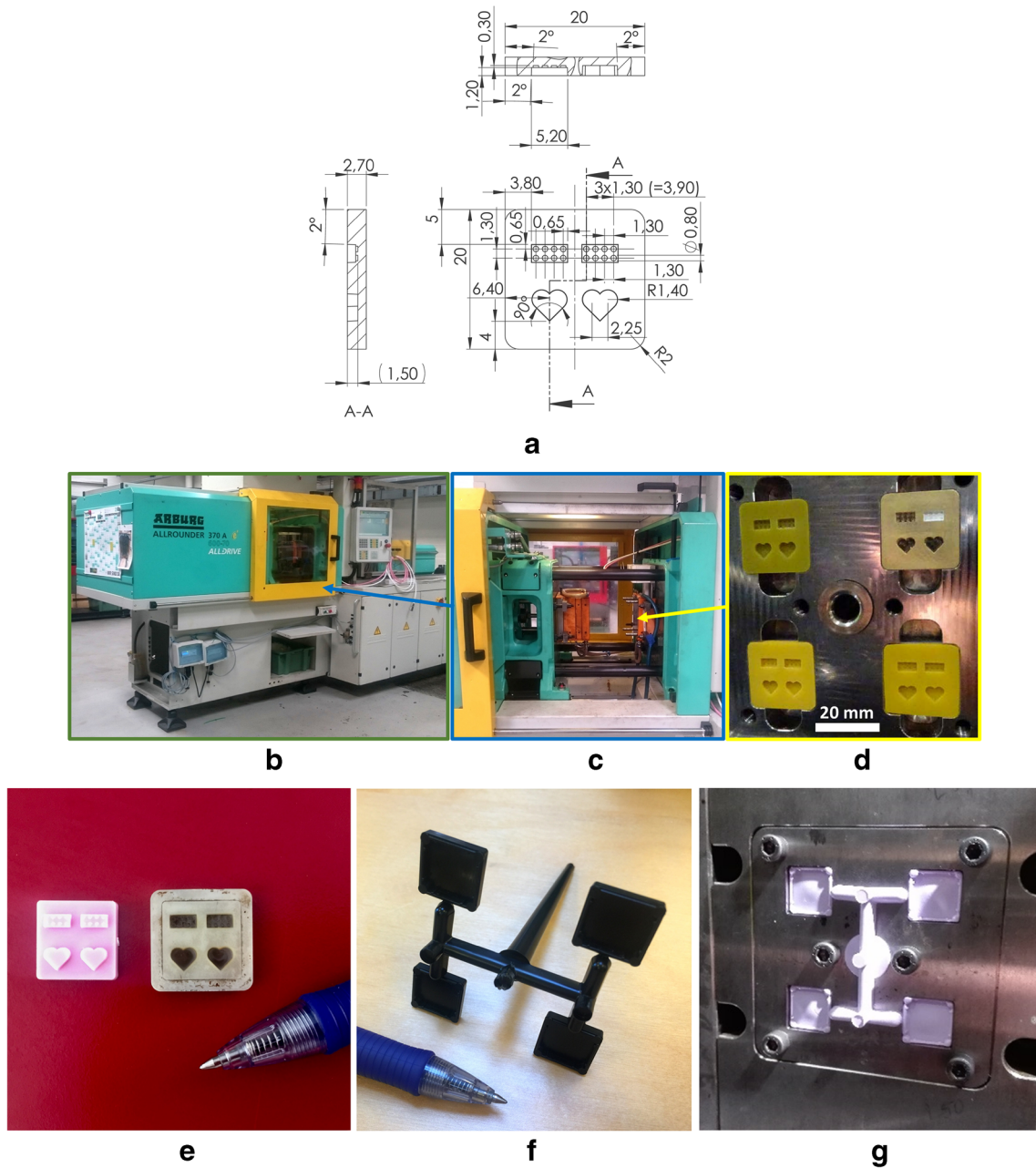
Fig. 2 **a** Mold cavity inserts are considered in this study (adapted from [6]); **b** injection molding machine; **c** injection molding tool; **d** four additively manufactured inserts assembled into the molding tool; **e** plastic part produced by injection molding (left) using the tool with the additively manufactured insert (right); **f** molded component produced in each molding cycle including four part, runners, gates, sprue; **g** complete molding in the mold before ejection

(right) are shown. The molded test part is a cuboid with dimension of $20 \times 20 \times 2.7$ mm^3. In each injection molding cycle, four molded parts are produced (see Fig. 2f, g).

3 Methodology

To provide a thorough understanding of AM and its adoption in the industry is important to evaluate the technology from a cost/benefit perspective. Such analysis is the quantitative tool to be used by top management for assessing the investment in the technology from a cost perspective [12, 13]. Moreover, understanding the cost components that in the past mostly affected the price to fabricate an object reveals opportunities for the future. Therefore, it follows that the cost to manufacture an object is one of the factors that influence managers in deciding whether or not to implement a new technology [12, 13].

AM cost models that are available in literature start under the idea that the technology is meant to replace conventional

manufacturing. Instead, the aim of this paper is to thoroughly analyze the creation of synergies between AM and conventional manufacturing. Therefore, it is essential creating an understanding of what would be the cost of AM as supportive technology rather than a replacement for injection molding.

Review of literature, cost models, and application cases in companies belonging to different sectors, all reveal that when AM is used to replace injection molding; it is cost-effective but only up to low production volumes [8–11]. Only few parts can be fabricated before AM becomes economically disadvantageous, and manufacturers are forced to switch to conventional manufacturing technologies. Figure 1 shows the AM investment curve when used to replace injection molding and when it is integrated in the injection molding process chain. Figure 3 shows a conventional cost per part comparison based on the use of injection molding and AM technologies for direct part production.

AM for production of single units requires a low initial investment, but the cost rises steeply with an increase of the production quantity. On the contrary, the injection molding as fabrication method is characterized by a conspicuous initial investment, which is then followed by a relatively low cost to manufacture a part. Therefore, the break-even-point in this scenario is equal to a small batch manufactured. It follows that manufacturers have to switch quickly to the injection molding in order to reach a cost effective solution for mass production.

The graph in Fig. 1 also demonstrates that the transition curve of AM when applied to create synergies with conventional manufacturing is gradual compared to the steep transition curve of AM when it replaces injection molding. Moreover, the integration of AM in the injection molding process chain for fabrication of tooling, as it will be further analyzed in this paper, points out that a much larger quantity can be manufactured. Application of AM for tooling production makes the technology cost-effectiveness for much larger production quantities even though fabrication of complex and time lavish mold inserts require a higher initial investment. The discussion about the economics that characterize AM continues in the following sections where the cost model estimation for AM is presented.

4 Additive manufacturing cost model

A cost model for the vat-photopolymerization technology, DLP [1], has not at this time been developed or discussed in literature yet. In this section, a cost estimation model for an insert manufactured with DLP technology is introduced.

The cost of an AM part manufactured with DLP technology is made up of five main cost elements: (a) pre-processing cost; (b) build cost; (c) material cost; (d) post-processing cost; and (e) overhead cost, as shown in Eq. (1):

$$C_{\mathrm{DLP}} = C_{\mathrm{pp}} + C_{\mathrm{pr}} + C_m + C_{\mathrm{pp}} + C_{\mathrm{ov}} \tag{1}$$

C_{DLP} is the unit cost for parts fabricated on the DLP machine (€/part), C_{pp} the unit cost for pre-processing (€/part), C_{pr} the unit cost for manufacturing a part (€/part), C_m the unit cost for material (€/part), C_{pp} the unit cost for post-processing (€/part), and C_O the unit cost of overheads (€/part) (see Table 1).

Equation (2) describes the cost for pre-processing activities that is affected among others by the part size, desired level of surface finish to achieve, material selection, and part orientation.

$$C_{\mathrm{pp}} = \frac{C_{\mathrm{Op}}}{N} \times T_{\mathrm{SW}} \tag{2}$$

The hourly operator cost including overheads is defined as C_{Op}(€/h), N is the number of parts that can be printed in the same build, and it depends on the size of the building envelope and the part orientation chosen. T_{SW} (hour) is the time used to setup the print job and chose the initial setting.

In order to estimate the cost to print a part, it is considered a simple mathematical relation between the machine cost per hour and the time spent to build a part as shown in Eq. (3):

$$C_{\mathrm{Pr}} = C_h^M \times \frac{T_B}{N} \tag{3}$$

where C_h^M is the hourly cost of the DLP machine (€/h), T_B is the printing time (hour). It is important to highlight that it is possible to incur in some errors during the printing of a part; hence, it is chosen to account for possible failures in the building through the use of the factor $\delta = [5\%, 20\%]$. Previous studies show that errors during the printing process can be linked with the experience of the operator that is handling the machine [15]. It was then chosen to set the build error at 5% for an experienced operator and 20% for operators that do not have a high degree of experience with DLP. The error factor delta is introduced in the building time as follows: $T_B = T_B/(1-\delta)$. Considering that N parts can be built in the same build, the time to complete the build is distributed over the number of parts manufactured simultaneously. Equation (4) describes the mathematical expression used to calculate the hourly cost of the machine.

$$C_h^M = \frac{C_I}{Y} \times \frac{1}{\sigma \times H} \tag{4}$$

C_I is the investment cost in the machine (€), Y is the machine lifetime (year), σ is a factor attributed to the machine utilization (%), and H is the total number of hours the machine can work in a year (hour/year).

Fig. 3 Comparison of cost per part between injection molding, SLA, FDM (fused deposition modeling), and selective laser sintering (SLS) when applied for direct part production (adapted from [9])
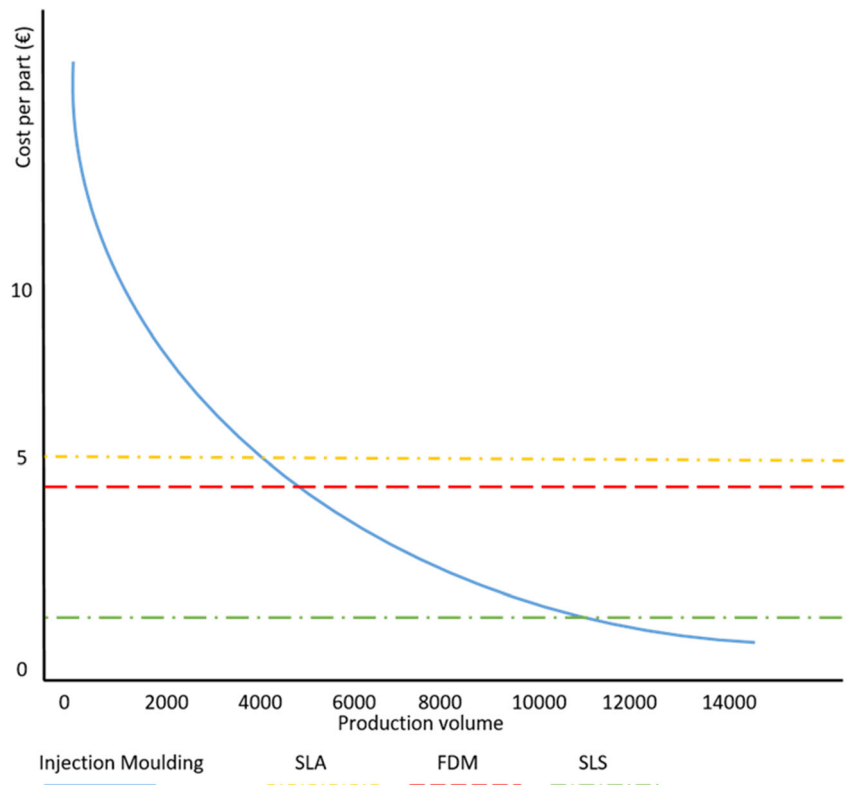
Cost for the material used in the printing process is estimated starting with the price of material per volume unit and multiplied for the total volume of the part in the build as shown in the equation below.

$$C_m = C_{lt}^m \times V_b \tag{5}$$

C_{lt}^m is the cost of material per liter used (€/l) and V_b is the total volume of the build that includes the volume of a part, support structures, and materials wasted during the printing process. Based on the equipment employed in the considered case, the total volume filled by the part in the vat is around 70% of the total volume used in the build. Therefore, the total volume used in the build, V_b can be estimated applying Eq. (6a, 6b).

$$V = V_{part} + V_{support} + V_{waste} \tag{6a}$$

$$V = \frac{V_{part}}{0.7} \tag{6b}$$

$V_{support}$ is the volume used for support structures in the build (in liters), V_{waste} is the amount of material that is waste (in liters).

Equation (7) breaks down the cost for post-processing activities, which includes removal of support material, post-curing, dry, and machining the part.

$$C^{pp} = \frac{C_{Op} \times T^{pp}}{N} \tag{7}$$

The time to post-process the part T^{pp} (hour) is the sum of the time to remove support material T_{SR}, time to post-cure T_{pc}, time to dry the part T_{pd}, and the time required to machine the part T_{Mc} as shown in Eq. (8):

$$T^{pp} = T_{SR} + \alpha \times \left(T_{pc} + T_{pd} + T_{Mc}\right) \tag{8}$$

Since the post-processing activities can be applied to more than one part at the same time, the total time used for post-processing is distributed over the number of parts that are printed in the same build, N. Moreover, to account for the time the operator is required to post-process DLP parts, the factor α (%) is used.

The last cost component considered in the model is the cost for overheads. A previous cost model [8] did not considered the overhead cost by assuming that their contribution is less than 1% of the total unit cost. However, a more recent cost model [10] that was built based on the model of [9] discussed the importance of overheads cost that account for a 10% of the total unit cost. Therefore, it is chosen to have an accurate

Table 1 Detailed cost breakdown for DLP manufactured parts considering different scenarios

Description (unit)	Variable symbol	Considered values and consequent cost scenario								Notes
		(min; max)	A	B	C	D	E	F	G	
Parts per build (N)	N	1; 15	15	4	3	3	2	2	1	Given by the size of the AM machine's building envelope, the part volume and the part orientation
Operator cost (€/hour)	C_{Op}	67;.20	67.20	67.20	67;.20	67.20	67.20	67.20	67;.20	Hourly cost rate for an operator including overheads and administrative costs
Setup time (min)	T_{SW}	15; 20	15.00	17.78	15.98	15.97	17.82	19.08	20.00	Time to setup the print job, chose the initial AM machine settings, part orientation and support structures (if needed)
Pre-processing cost (€)	C_{pp}	1.12; 22.40	1.12	4.81	5.65	5.96	9.39	10.05	22.40	Cost to prepare the machine for manufacturing the part represented by the cost of the operator to setup the AM machine ready for production, chose the correct part orientation, material, level of accuracy
Purchase machine (€)	C_I	90.000	90.000	90.000	90.000	90.000	90.000	90.000	90.000	Cost for the investment to purchase the DLP machine
Depreciation time (year)	Y	3; 7	7	6	6	5	5	5	3	Number of year the machine will be used before its technology becomes obsolete
Utilization (%)	σ	40; 80	80	64	76	63	68	62	40	Percentage of time the machine is not idle
Hours per year (hour)	H	8760	8760	8760	8760	8760	8760	8760	8760	Total number of hours the machine could work in a year
Machine cost per hour (€/hour)	$C_h^M i$	1.83; 8.56	1.83	2.68	2.25	3.28	3.03	3.30	8.56	Hourly cost rate for the machine use
Time to build (min)	T_B	400	400	400	400	400	400	400	400	Time needed for completing the manufacturing process
Printing failure (%)	δ	5; 10	5	5	9	9	9	9	10	Percentage of time the machine fails when in use
Production cost (€/part)	C_{Pr}	0.86; 63.42	0.86	4.69	5.47	8.02	11.06	12.07	63.42	Production cost per part given the hourly machine cost, the time to build and the amount of parts that

Table 1 (continued)

| Description (unit) | Variable symbol | Considered values and consequent cost scenario | | | | | | | | Notes |
		(min; max)	A	B	C	D	E	F	G	
										can be printed simultaneously
Productivity (part/hour)	P	0.15; 2.25	2.25	0,60	0.45	0,45	0.30	0.30	0.15	Number of parts that can be manufactured in one hour
Cost of material (€/l)	$C_{M_{Kg}}$	400	400	400	400	400	400	400	400	Material cost for the photopolymer blend per volume unit (liter)
Part volume (cm^3)	V_{part}	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Volume occupied by the single part (one insert)
Volume of the build (l)	V	1.5×10^{-3}; 22.5×10^{-3}	22.5×10^{-3}	6.0×10^{-3}	4.5×10^{-3}	4.5×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	1.5×10^{-3}	Volume of the build considering the number of parts that can be manufactured simultaneously, including support structures
Material cost (€)	C_M	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	Material cost per part
Support removal (min)	T_{sr}	30; 45	30	42	30	34	36	42	45	Time to remove support material
Post-curing time (min)	T_{pc}	15; 30	15	15	23	26	24	24	30	Time to photo-cure the AM insert in a light oven
Drying time (min)	T_{pd}	15; 30	15	15	23	26	24	24	30	Time to dry the part and ensure its complete solidification
Machining time (min)	T_m	15; 30	15	15	23	26	24	24	30	Time for machining the parts and reach the required accuracy and surface finish for assembly the insert into the injection molding tool
Manual labor post-processing (%)	α	10; 25	10.00	10.00	10.00	12.84	10.61	10.94	25.00	Percentage of time required by the operator for the post-processing activities listed above
Post-processing time (hour)	T_{Pp}	0.125; 0.563	0.125	0.145	0.165	0.196	0.188	0.205	0.563	Total operator time for a part for being post-processed
Post-processing cost (€)	C_{Pp}	2.58; 75.60	2.58	12.94	13.78	16.39	24.33	27.67	75.60	Operator cost for post-processing
Maintenance cost per year (€/year)	C_{Me}^{y}	400	400	400	400	400	400	400	400	Cost for maintenance services (based on industry average)
Maintenance cost per hour (€/hour)	C_{Me}^{h}	0.03; 0.76	0.06	0.07	0.06	0.16	0.07	0.07	0.11	Hourly re-scaling of the maintenance fee
	C_{Me}	0.05; 0.13	0.03	0.12	0.13	0.15	0.22	0.24	0.76	

Table 1 (continued)

Description (unit)	Variable symbol	Considered values and consequent cost scenario								Notes
		(min; max)	A	B	C	D	E	F	G	
Maintenance cost per part (€/part)										Maintenance fee per part
Machine electricity consumption (KWh)	E	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	Electricity consumption by the AM machine
Cost of electricity (€/KW)	C_e	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	Electricity cost per KW used
Cost of electricity per part (€/part)	C_{el}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	Part allocation of the electricity cost
Cost for m² of surface area per year (€/m²/year)	C_s	17	17	17	17	17	17	17	17	Cost of yearly space rental per unit of surface area for the area occupied by the DLP machine
Surface area used by the machine (m²)	C_{sr}	10	10	10	10	10	10	10	10	Workshop floor surface area occupied by the DLP machine
Cost of surface area per part (€/part)	C_{Ov}^h	0.01; 0.32	0.01	0.05	0.06	0.07	0.10	0.11	0.32	Cost of space rental for surface area unit per part
Overhead cost per part (€/part)	C_{Ov}	0.05; 1.24	0.05	0.21	0.24	0.28	0.40	0.42	1.24	Sum of overhead costs distributed over the number of parts
Cost per part (€/part)	C_{DLP}	5.20; 163.26	5.20	23.25	25.75	31.25	45.78	50.82	163.26	Sum of all cost contributions for the manufacturing of a part on a DLP machine

estimation of the cost of a part manufactured with DLP and overheads, cost are introduced in the following equation:

$$C_{ov} = \frac{C_{el} + C_{Sr} + C_{Me}}{N} \quad (9)$$

However, it was chosen not to consider logistics costs due to the specific company setup of the industrial partner of this project where both AM and CNC machined mold inserts are manufactured in-house.

The cost for electricity usage C_{el} (€/part) is calculated considering the amount of electricity consumed by the machine E (KWh), the cost per kilowatt of electricity consumed C_e (€/KW), and divided by the number of parts manufactured in a hour P (part/hour) as shown in Eq. (10).

$$C_{el} = \frac{E \times C_e}{P} \quad (10)$$

It follows that the cost to rent the facility C_{Sr} (€/part) is estimated by multiplying the amount of space used by the machine S (m²) and the cost for square meter used C_s (€/m²), and divide the whole by the number of hours the machine works in a year ($H \times \sigma$), which is multiplied by the amount of parts manufactured in a hour P. Equation 11 summarizes what just described.

$$C_{sr} = \frac{S \times C_s}{\sigma \times H} \times P \quad (11)$$

Lastly, the maintenance cost C_{Me} (€/part) is usually charged as a service cost from the machine manufacturer and equal to 10% of the machine purchase price. The yearly maintenance cost C_{Me}^y (€/year) is then distributed over the hours the machine works in a year ($\sigma \times H$) and multiplied by the number of

parts per hour H. Equation (12) show the mathematical equation used to estimate the maintenance cost per part.

$$C_{Me} = \frac{C_{Me}^y \times P}{\sigma \times H} \qquad (12)$$

5 Injection molding cost model

The cost components of injection molding were investigated to understand what the main sources of costs are to manufacture plastic molded parts and quantify the impact of AM to lower the total cost. Three are the main cost elements that largely contribute to the cost of a molded plastic part: (a) tool cost C_T; (b) material cost C_M; and (c) production cost C_{Pr} (all expressed in €/part) (as shown in Eq. (13)).

$$C_{IM} = C_T + C_M + C_{Pr} \qquad (13)$$

where C_{IM} is the unit cost of a molded part (€/part), C_T is the total tooling manufacturing cost per part (€/part), C_M is the material cost (€/part), and C_{Pr} is the processing cost (€/part).

Part complexity, size, and geometry are among the main factors that affect the cost of a molded part together with the material selection. Among those, the production volume is another factor that highly affects the cost per part as depreciating the highly expensive investment in tooling for a small or large volume can greatly influence the cost per part. Brass and aluminum mold inserts require an expensive investment; hence, at larger production volumes, the ratio of cost due to tooling decreases as the investment is depreciated over a larger production volume.

Mold cost is mainly influenced by the cost of the mold base and the cost to machine the inserts. Based on the number of cavities in the mold, an equivalent number of inserts are machined. Inserts are dependent on the part size and geometry, and on the complexity of fabricating cavities and cores and the level of surface finish required. The mold cost is calculated as shown in Eq. (14):

$$C_T = \frac{C_{MB}}{LC} + \frac{C_{In} \times n}{B} \qquad (14)$$

where C_{MB} is the cost of a mold base (€), C_{In} is the cost to manufacture one insert (€/insert), n is the number of cavities, LC is the life cycle of the mold base (parts), and B is the batch size or number of injection cycles for which the inserts is used for.

Material cost is a major factor to take into consideration. An appropriate selection of materials will positively affect the usability of final parts, and the life cycle of the inserts. Molded part costs also depend on the choice of materials. The main components of material cost are the price per kilogram of

material used and the weight of plastic material required to mold one part.

Part weight is calculated considering the sum of the part, runners, and sprue weights to account for the material used to mold the part, but also wasted for the runners and sprues as calculated in Eq. 15:

$$C_M = C_{M_{Kg}} \times W \qquad (15)$$

where $C_{M_{Kg}}$ is material cost per kilogram of material used (€/kg), and W is the total weight in kilogram.

Part processing cost is the sum of the expense related to the amount of time the operator spends to run the injection molding machine and the cost of the machine per part. Equation 16 determines the processing cost per part:

$$C_{Pr} = C_h + \frac{C_m}{Cap_h} + \frac{\alpha \times C_O}{Cap_h} \qquad (16)$$

where C_h is the cost to setup and run the injection molding machine (€/part) and is calculated as the production of hourly operator cost and the sum of time to setup a mold and the time the machine is not running because the mold has been extracted, distributed over the batch size B. Cap_h is the hourly capacity of the machine (in number of parts per hour) considering that a mold fabricated with n cavities will produce n parts over the cycle time. C_O is the hourly cost of an operator (€/hour). The factor α is again used to account for the actual percentage of time the operator is involved in the use of the machine. According to industry standard typical of an injection molding facility, an average utilization (α) of the workers equal to 20%. Equations (17) and (18) introduce the calculation of C_h and Cap_h:

$$C_h = \frac{(T_S + T_D) \times C_O}{B} \qquad (17)$$

$$Cap_h = \frac{3600 \times n}{CT} \qquad (18)$$

To conclude, T_S defines the time used to setup the machine (in hours), while T_D accounts for the time the machine is down for mold changeover or maintenance (in hours), and CT is the cycle time of the process (in seconds).

Table 2 presents a detailed cost breakdown for injection molding when the insert with micro features shown in Fig. 3 is CNC machined and additively manufactured respectively.

6 Results

In the previous sections, a model to estimate the economics of AM aiming to develop a cost estimation method that describes the production costs associated with fabrication of inserts for injection molding has been introduced. The objective of the economic analysis is to highlight the cost advantage of

Table 2 Cost per molded part using CNC and AM inserts for injection molding tool. Notes: (*) this figure refers to the cost of a standard machining operation for the considered tooling insert design; (**) this figure refers to cost scenario D in Table 1

Cost component	Variable symbol	Value		Notes
		CNC insert	AM insert	
Mold base (€)	C_{MB}	23,521.51	23,521.51	Investment to purchase a mold base for the assembly of 4 inserts
Mold block lifetime	LC	2,000.000	2,000.000	Expected life time of the mold base in number of injection molding cycles
Insert (€/insert)	C_{In}	332,66 (*)	31,25 (**)	Cost of one mold insert in aluminum or brass (CNC machined insert) or in photopolymer (DLP AM technology)
№ of cavities (#)	n	4	4	Number of cavities in the injection mold tool
Batch size (parts number)	B	100	100	Size of the batch in number of injection molded parts for which the mold's inserts are produced
Tool cost (€/part)	C_T	13.31	1.25	Cost per part associated to the investment for tooling
Material per kg (€/kg)	$C_{M_{Kg}}$	1.74	1.74	Cost of the injection molding plastic per unit of mass
Mass (g)	W	5,0	5,0	Mass of the complete molded part produced in each molding cycle (including sprue, runners, gates)
Material cost (€/part)	C_M	0.009	0.009	Cost per part of to the plastic used for injection molding
Setup time (hour)	T_S	1	1	Time to setup the injection molding machine to start production
Down time (hour)	T_D	1	1	Average time the machine is idle due to mold and/or insert changeover, scheduled or unpredicted maintenance during a pilot production of 100 parts
Operator cost (€/hour)	C_O	67.2	67.2	Hourly cost of the operator working and supervising the injection molding machine during pilot production (including overheads and administrative costs)
Handling cost (€/part)	C_h	1344	1344	Cost per part of setup and machine idle time calculated as hourly operator cost and distributed over the batch size B
Cycle time (s)	CT	20	50	Injection molding cycle time taking in consideration mold closing/clamp, filling phase, packing phase, cooling phase, mold opening and part ejection
Hourly capacity (part/h)	Cap_h	720	288	Machine hourly productivity based on cycle time and number of mold cavities/mold inserts
Injection molding machine cost (€/h)	C_m	12.6	12.6	Hourly cost of the injection molding machine
Production cost (€/part)	C_{Pr}	1.38	1.43	Production cost per part (considering a pilot production batch of 100 parts)
Cost per part (€/part)	C_{IM}	14.70	2.69	Cost of a part molded with an insert produced by CNC machining or additively manufacturing respectively

integrating AM in production environment aiming at decreasing the operational cost tied up with the cost of tooling for injection molding.

The economic analysis of AM highlights the cost advantage of photopolymer inserts when used for low/medium production volumes. It is interesting to investigate how the situation would change for higher production volumes and up to what production volume AM results cost-effective compared to CNC machining.

This section is structured presenting first a discussion of the cost advantage that are enabled by AM integration. The robustness of the cost estimation model is investigated considering how the adoption of AM would change in case the batch size is increased calculating the break-even point between the two scenarios.

First, it is necessary to calculate the cost of a part produced with DLP technology as shown in Table 1. Seven different cost scenario based on actual manufacturing cases are

presented to show the effects of the different cost elements on the final cost per part produced by the DLP AM technology. Secondly, the cost of inserts manufactured with DLP are used to calculate the cost per molded part as shown in Table 2. For this purpose, the cost scenario D, representing a likely and intermediate case among the different cost settings considered, is used as input for the final cost of the molded part.

An analysis of the cost components of an injection molded part shows that the cost for CNC machining a tools account for 90% of the total unit cost (i.e., $C_T = 13.31$ € out of $C_{IM} = 14.71$ €). The use of AM for fabrication of soft tools decreases the tooling cost by 91% when the batch size is 100 molded parts. Processing cost increases by 4% when AM inserts are used (from 1.38 € to 1.43 €). The longer cooling time required by the photopolymer inserts to cool down efficiently the injection molded part (50 s when using an AM insert instead of 20 s when using a CNC insert) is the main cause for the higher processing cost.
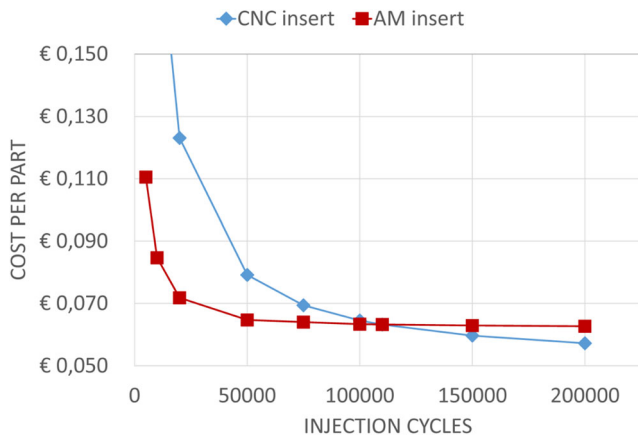
Fig. 4 Break-even-analysis of AM and machined inserts for injection molding

Fig. 5 Cost per plastic part comparison injection molded with CNC machined and AM inserts (batch size: 100 parts)

A break-even-analysis (BEA) was performed to assess and evaluate the economical trade-off of integrating AM in the IM process chain. Figure 4 shows that with a batch production size up to 110,000 parts, the unit cost for parts molded with the additively manufactured insert amounts to €0.06 and photopolymer inserts are favorable compared to machined inserts up to such production volume.

This analysis shows that is possible to mold parts up to medium production volumes without incurring in extra operating costs due to increase cost of tooling. For larger production volumes that are common in mass production and reach the millions of cycles, it is advisable to switch tooling technology and use machined inserts in tool steel. The longer lifetime of the machined inserts allows depreciating the tooling costs over a larger production volume and decrease the number of changeover needed by the AM inserts. Instead, he cost advantages linked to molding small/medium production series with photopolymer inserts prove and show the potential cost savings in supporting IM with AM.

One of the factors that influence the BEA of AM inserts is the size of the insert, which acts as a production constraint in fabricating a high number of inserts in the same AM build batch. Moreover, the size of AM inserts and the material used to produce them allow for a shorter amount of time spent for post-processing activities that decreases the overall cost of additively manufactured parts.

7 Discussion

The cost model proves the potential cost savings in applying AM inserts in injection molding serial production when small batches of parts are to be molded. For small batch with size up to 110,000 injection cycles, the largest cost component is the investment in tooling. Figure 5 shows how the three injection molding cost components (tool, material, and processing costs) affect the total cost per part when inserts are machined
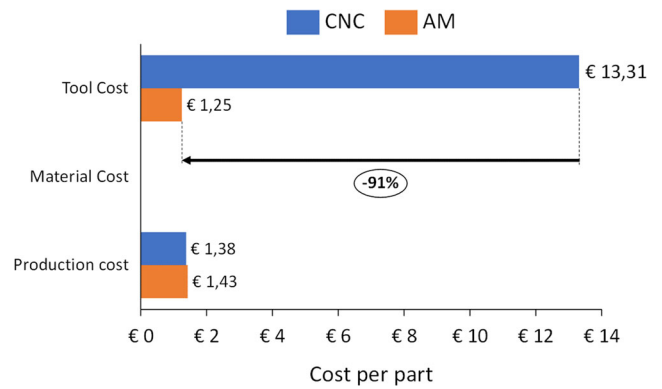
or fabricated with AM. For a part molded with the insert manufactured in brass or aluminum by CNC machining, the cost for tooling can be up to 80–90% of the total cost per part, while with AM inserts is 54% of the total cost in the considered case when AM is used for prototyping and the production batch is equal to 100 shots (i.e., $C_T = 1.25$ € out of $C_{IM} = 2.69$ €). The final cost part decreases by 82% from 14.71 € for parts molded with a CNC insert down to 2.69 € for parts molded with an AM inserts (see Table 2). Increasing the batch size and consequently changing the technology for final tool production of larger molding volumes (100,000 parts or higher) allows to depreciate the cost of tooling over a higher number of parts. When increasing the batch size, it is critical to consider the tool lifetime, which for the brass or aluminum inserts can reach 2,000,000 shots, while for the AM inserts has reached in this study a lifetime of 10,000 injection molding cycles.

Moreover, the increase in processing cost in AM inserts is due to the longer cycle time required to efficiently cool down the insert, which is 2.5 times higher than the cycle time observed with brass inserts. The longer cycle time when parts are molded using the AM insert has to be taken into account in the cost model to assess by how much the total production lead time is affected by such longer cycle time over the long run. A greater advantage can be obtained in case the integration of AM for inserts production reduces the manufacturing lead time for new parts and speed the product development phase.

The simulation case scenario showed that in case AM inserts are used the time required to manufacture the necessary amount of inserts, carry out the post-processing activities, assemble the inserts into a four-cavity mold, and perform 100 injection shots equal to 61.7 h. When the inserts are CNC machined more than twice, the time is required since the observed lead time was equal to 182.6 h. Therefore, it is possible to notice that using AM inserts leads to a 66% lead time reduction in the product development phase. Such lead time reduction means that for a low production volume typical of the product development phase, integrating AM can reduce the manufacturing lead time by at least 5 days and streamline the entire process.

Lead time reduction in the pilot production leads to a higher operational effectiveness that is transformed in a competitive and cost advantage. Through the reduction of the time required to fabricate inserts, it is possible to quickly test new part designs and evaluate them in less than half of the time that it is required with conventional tooling technologies. Even though the cycle time required to mold parts when AM inserts are used 2.5 times higher due to the longer cooling time that is necessary to prevent thermal aging of the inserts, the time savings in the overall process are remarkable. Moreover, if it is taken into consideration that few design iterations are usually necessary before the final version is obtained, then the advantage of using AM inserts is even greater.

8 Conclusion

This research contributes to the analysis and development of additive manufacturing adoption within the conventional manufacturing process of injection molding. It is of a particular interest in order to facilitate companies to research how to exploit the advantages that AM can offer. This article elaborates on the possible synergies between AM and conventional manufacturing to create added value by decreasing operational cost in the pilot production, particularly useful in the product development phase.

The impact of layer manufacturing technologies has been a largely discussed topic in the literature, where it has been argued that the way products have been manufactured until now; it is meant to be overturned by AM. However, this work focused on an alternative scenario, in which AM is not conceived as a disruptive technology but instead as a set of processes that have the potential to improve a conventional production process (i.e., injection molding in this case) instead of replacing it.

Alongside, this research has quantified the benefits of additive manufacturing integration for value creation with respect to cost and lead time reduction. In this way, the work represents a source of novelty in the practice of analyzing additive manufacturing to optimize a supply chain, while considering at the same time the value chain. Such analysis helps to identify the primary key trends in additive manufacturing adoption and the main challenges that organizations need to address in order to determine how additive manufacturing can deliver value to the production process chain.

One of the most important points that emerged from the analysis is the impact of additive manufacturing in increasing the operational efficiency and substantially decreasing the manufacturing cost. These aspects have been exemplified in this work through the integration of additive manufacturing for soft tooling in an injection molding process chain.

The research has demonstrated the possibility to reduce manufacturing cost in terms of cost per part by 82% (from 14.70 €/part down to 2.69 €/part in case of a batch of 100 parts) and streamline the whole product development phase by obtaining a much faster and flexible process chain with a considerably shorter lead time. On-demand production of injection molding tools is now a reality. Through the use of photopolymer inserts produced by DLP, it is possible to reduce the production lead time of tooling by 66%. The average weeklong time required to machine inserts can be substituted by a 2-day lead time when additive manufacturing is used. Such faster and more flexible product development phase allows achieving a higher level of operational flexibility through the creation of a quicker, cost-effective, and more agile production system. New part designs can be tested quickly; hence, manufacturing companies have the possibility to speed their time to market reducing the whole product development phase.

Moreover, the investment in tooling is remarkably reduced as the cost for manufacturing mold inserts are extremely decreased. The inserts manufacturing cost is reduced from 1331 € to 125 € (i.e., 91% decrease) of the CNC machined insert and AM insert respectively. On-demand production of injection molding tools is now a reality, and the investment in tooling is remarkably decreased as the cost for manufacturing mold inserts is substantially decreased.

Even though AM has the potential to optimize the operational efficiency of a firm, it is important to highlight that the current technological limitations can still slow down its adoption in some department and areas of the job floor. A reflection on the current restrictions of the technology is necessary to correctly establish where and how layer manufacturing techniques can be applied, for example, determining their suitability when more restrictive production requirements and smaller product tolerance specifications are defined. Consequently, the main areas where the technology will need to improve are identified and discussed throughout the cost estimation model, which highlights the key cost components and their impact on production cost and lead time.

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