LIFE CYCLE APPROACH TO SUPPORT TOOLING DESIGN DECISIONS

Inês Ribeiro [1], Paulo Peças[1] and Elsa Henriques[1]
(1) IDMEC, Instituto Superior Técnico, TULisbon, Portugal

ABSTRACT
The design and production of tools is a time consuming, technically difficult and expensive activity. Moreover, tool design selection greatly affects the efficiency of the manufacturing process of final parts in which they are used. Sometimes the least expensive tool does not lead to the least resource demand part production. It is then necessary to shift the paradigm from the cost of the tool as the main decision factor to the tool life cycle cost and even to other aspects not included in conventional costing. In this context, this research presents a new methodology to approach decision making in tooling design. This methodology captures not only the conventional costs, but also more intangible tooling aspects such as reliability. Moreover, as different stakeholders value distinct aspects of the production process, these different perspectives are modelled and quantified in order to form a structured comparison between tooling design alternatives. The methodology will be applied to a case study in the moulding industry in order to exemplify its application.

Keywords: Tool Design Life Cycle Cost, Injection Moulds, Process-based cost models

1 INTRODUCTION
Tools, and in particular injection moulds, are at the core of most production systems, as they affect the final product and the production equipment and machinery. The stability of the production process, as well as the quality of the product, are inevitably dependent on the quality of the mould. In addition, the selection of the mould design deeply affects the injection moulding process in terms of energy and material resources consumption. Current strategies to cope with the engineering design of injection moulds are mainly focused on a short phase during which tool makers have direct access to the moulds – from design to manufacturing and testing. The subsequent phase of mould usage and maintenance, a much longer period, is usually the responsibility of the tool user. Therefore, during the mould design phase the main aim is to identify the design solution that, based on the available capabilities and knowledge, meets the explicit specifications of the client. In the current industrial approach there is no space for the search or discussion of alternative solutions of mould design that can benefit the tool maker, the part producer and other stakeholders.
Moreover, frequently the least expensive mould does not lead to the least expensive part option, if the subsequent part manufacturing processes in which the mould is used are considered. It is then necessary to shift the paradigm from the cost of the mould as the main buying decision factor to the mould life cycle cost and even to other performance aspects not normally included in conventional costing. Hence, a more complete knowledge of the mould life cycle, integrating management, costing, design and process engineering aspects is necessary to fully understand the impact of the initial selection of mould design and to enhance the efficiency of its life cycle [2]. Furthermore, knowing that designers have a key responsibility in deciding technical, economical and environmental issues,
[3, 4], it is extremely important to develop guidelines for mould life cycle evaluations and to review mould design selection based on life cycle principles. This has motivated several researchers to develop methods and decision tools that aim to estimate costs, environmental and other performance indexes of products in early life cycle stages – that is, before production commitment. These methods comprise costing tools, namely Life Cycle Cost (LCC) [5,6] and process-based cost models [7,8], environmental assessment tools, namely Life Cycle Approach (LCA) [9,10] and even more comprehensive tools comprising several aspects of the Life Cycle of a product – Life Cycle Engineering, Life Cycle Design, Life Cycle Management, eco-design, among others [11-14].
This paper presents a life cycle approach to assess the design phase of injection moulds and explores its potential in generating more informed design decisions. The proposed approach is driven by a LCC

methodology derived from process-based cost models, formulated for all the life phases of the mould. For this, engineering knowledge is used to model the involved processes and all the required resources (consumed or used) are estimated to compute the Life Cycle Cost of alternative design solutions for the mould. The main goal is to compare, during the mould design stage, the impact of alternative designs on the subsequent phase of mould usage. It should be noted that this type of models has been applied by researchers to several processes with different scopes, but always with the intent to compare alternatives – either in materials, processes or product architectures [15-18]. In this case two main models are integrated: the mould production model provides inputs to the mould usage model (injection moulding) according to the mould design options. Finally, in the last phase of this approach, the alternative designs are compared taking into account not only the cost, but also the performance of the mould, based on the preferences of the different stakeholders. The objective is to include these preferences in the cost models and hence to compute a subjective life cycle cost. In fact, in a real industrial context, decisions are not based only on tangible costs. Some aspects such as mould reliability, maintainability and injection cycle time, among others, have more relevance than what is usually reflected in conventional costs. Moreover, these preferences might be different for each stakeholder, and therefore it is interesting to identify and discuss the differences between alternative design options.

2 METHODOLOGY

2.1 General Approach

The approach proposed in this paper (Figure 1) aims to evaluate not only the mould cost, but also the impact of a mould design decision throughout its lifetime. In order to understand the future implications of early design decisions in terms of costs and other performance indicators, it is not enough to rely on a basic accounting system, it is also necessary to understand the whole process of consumption and use of valuable resources. Importantly, the evaluation of a specific design must take several aspects into account, such as the required technologies and resources, as well as reliability and capability/efficiency constraints. Therefore, it is necessary to better understand the mould lifetime and its contribution to the entire production process.

As this research is focused on dedicated tools, in particular plastic injection moulds, the first step is to explore alternative tool designs that are able to produce a specific part according to the requirements of the client. In the context of technically complex moulds, several solutions are often possible. Taking into account that such solutions might imply different production costs and might result in different performances of the mould during its usage phase, the best options are not always obvious and, moreover, depend on the perspective of analysis, for instance the mould producer, buyer or user point of views. Having chosen a set of design alternatives, the next step is to develop a process-based cost model that allows the estimation of the mould production costs. The following phase is the quantification of the effect of alternative designs on the performance of the mould during the injection phase, adding a new life stage to the process-based cost model. Depending on the part and on the specifications of the mould design, the costs to produce the part are modelled according to variations in cycle time, maintenance level, downtime, material waste, required injection machine, among other cost drivers. This approach correlates technological and production parameters with cost drivers and, subsequently, with resource requirements and respective costs, allowing enough flexibility to easily perform sensitivity analyses to variations in the mould design and in the injection moulding process, namely to the production volume. However, other aspects may affect the design decisions that are not fully captured in the estimated costs. For example, the reliability of a mould design affects the required maintenance and the injection machine downtime, which impact the tangible costs. However, the machine downtime may also affect the delivery time and the production schedule of other parts. The injection cycle time, which affects the production time, and the initial investment in tools, also have an intangible value that is not readily perceived in the costs. In order understand the importance of these intangible variables to the different stakeholders, a survey was undertaken among industrialists that aimed to identify important "qualities" that are not immediately translated into costs. For that, it is proposed a pair-wise comparison technique to evaluate these "qualities" from the point of view of the different stakeholders involved in the mould life cycle.

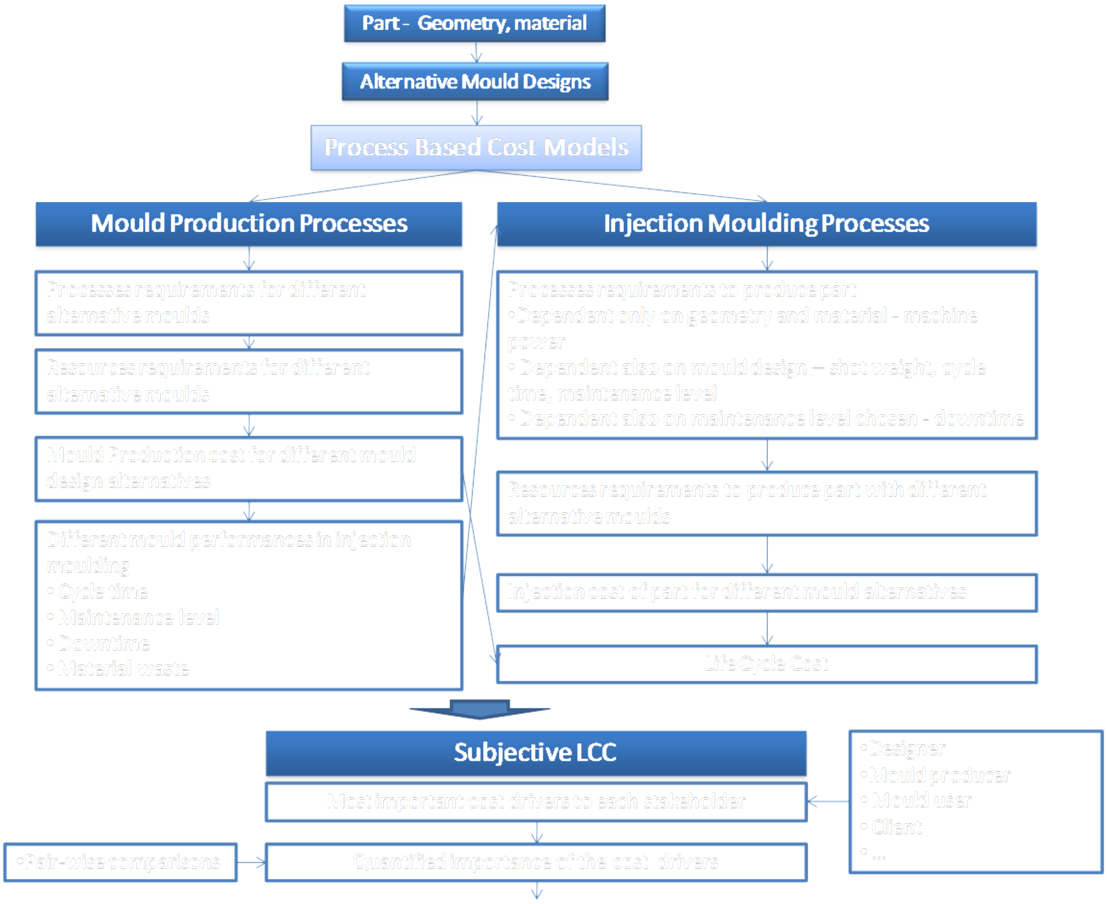

Figure 1. General Methodology

2.2 Modelling costs through the processes

With the objective of evaluating "all the costs associated with a product throughout the product's life" [5], the proposed methodology uses process-based cost models applied to each phase of the tool life cycle, which enables to track the influence of design variables on the cost drivers. However, this influence might be highly dependent on the production scenario in which the mould is intended to be used. For instance, in scenarios in which a high production volume is demanded, more productive (low injection cycle time) and reliable moulds are likely to be preferred, even though the design solutions for such moulds are usually more expensive if only their production costs are considered. The industries that use moulds have specific quality, performance and production expectations, which can be difficult to translate into explicit requirements. However, these expectations are important factors in mould decisions, together with principles of building resource efficient moulds over their life cycle.

Process-based cost models are a suitable approach to compare the effect of design and technological alternatives on the production cost. For this, the manufacturing process must be modelled, accommodating the alternatives under analysis, considering the net of influences between technologies, operations and economic based variables [15-18]. Starting from the description of the final product (part material and geometry), the processes involved in its production are modeled according to the required cycle time, resources (equipments and labor) specifications, etc. These can be obtained from theoretical and empirical correlations between the properties of the part and the technological requirements. By adding inputs regarding the operating conditions of a certain plant it is possible to build up the operations model. The next step is to compute the resource requirements regarding the operations model, such as the number of tools, equipments, operators, etc. Finally, having all the process or processes modeled and the estimates of the resources required to produce the part (or parts), by simply introducing price factors to each cost driver, the economical model is completed and the product cost computed (see Figure 2). The models developed in this research estimate the cost of the mould production and mould usage processes, allowing the evaluation of a mould design based on its impact on the unit cost of each injected part.

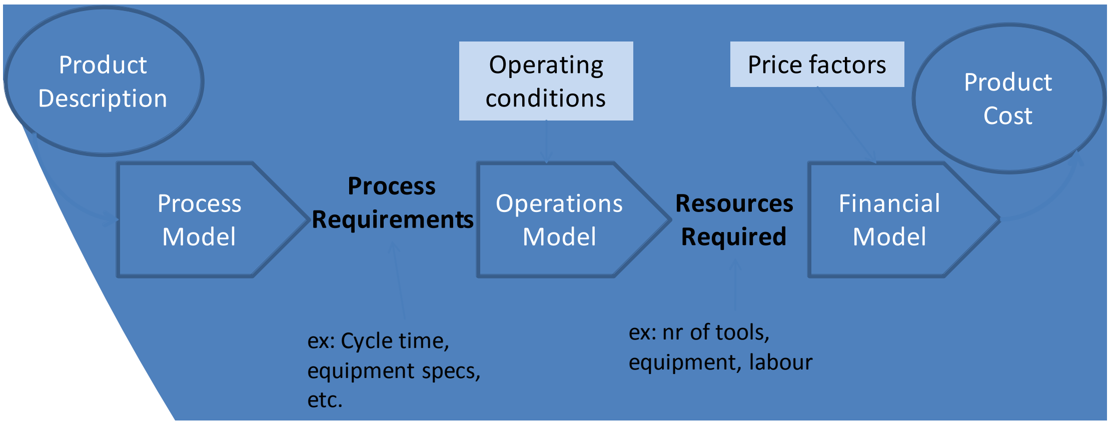

Figure 2. Process-based cost models

It should be emphasised that the object of study in this research is the mould. However since several mould designs may be used to inject a single part, their evaluation can only be done including the mould in use performance and understanding how it affects the part production costs. Therefore, in this study two main process-based cost models were built: the mould production and the injection moulding models. These are not independent models, since different tool design options generate different inputs to the injection moulding model, thus resulting in different part costs.

In the first phase the mould production process was modelled, from the design of mould components, to the machining technologies (milling, drilling, turning, grinding, EDM, wire EDM), finishing, assembly and laser engraving. In the second phase the injection moulding process was modelled linked to the first model. It considers the influence of the main design options, like the mould architecture, type of runners system, number of cavities and expected duration, on the process cost drivers. The mould architecture influences the required mould maintainability and, consequently, affects the maintenance cost and both the mould and machine downtime. The type of runner system affects the cooling time and consequently the injection cycle time. The number of cavities also affects the cycle time and the expected mould duration largely determines the number of injection cycles between major replacements of the moulding surfaces. Regarding the part specifications, the model is sensitive to the material and the geometry of the part, which affect the cycle time, the machine requirements and the downtime for a predetermined maintenance level. Finally, the process conditions regarding the chosen mould maintenance level (also dependent on the mould type, part material and part complexity), the part production volume and other exogenous variables related to the company operational and economical context are also considered.

2.3 Examples of relations between technological parameters and operational and financial variables

In order to exemplify the type of relations that enable a high degree of flexibility to the models, the equation used to calculate the injection cycle time is presented as an example. An empirical relation, largely accepted in scientific and technical communities, correlates the part material (injection and ejection temperatures and effective thermal diffusivity) and part geometry properties (thickness), depending on the mould runner system (hot or cool runners) and mould temperature, with the time required to cool the part inside the mould. This relation is given by [19]:

$$t_{cooling} = \begin{cases} \frac{s^2}{\pi^2 \alpha_{ef}} . ln(k.Y), \ hot\,runners \\ \frac{D^2}{23.14\alpha_{ef}} \, ln\,(0{,}692Y), \ cold\,runners \end{cases} \quad (1)$$

$$Y = \frac{T_{inj} - T_{molde}}{T_{ext} - T_{molde}} \quad (2)$$

Where s is the maximum part thickness [m], k is the part thickness coefficient ($K=4/\pi$ if $s \leq 3$ mm, $K=8/\pi 2$ if $s > 3$ mm) and α_{ef} is the average effective thermal diffusivity of the part material (µm2/s).

This cooling time is the main element of the total injection cycle time, being tacitly considered as 90% of the injection cycle time (the remaining time is needed to inject the fluid part material and to open and close the mould and to eject the part).This injection cycle time affects almost all cost drivers in the model, from energy and labour variable costs, to the fixed ones like machine and building use costs.
However, some relationships are not available in the literature, and need to be obtained from either experimental data or experienced-based knowledge from experts in the area. A simple example of data-based correlations regarding injection machines properties is presented in Figure 3. By collecting data from different machines, it is possible to correlate the machine tonnage (clamping force) with the machine acquisition cost (Figure 3). Similar relations were found for other machines properties, runners systems (depending on the type of runners, manifold, nozzles), mould plates (dependent on the type of plate and size) and other mould elements.

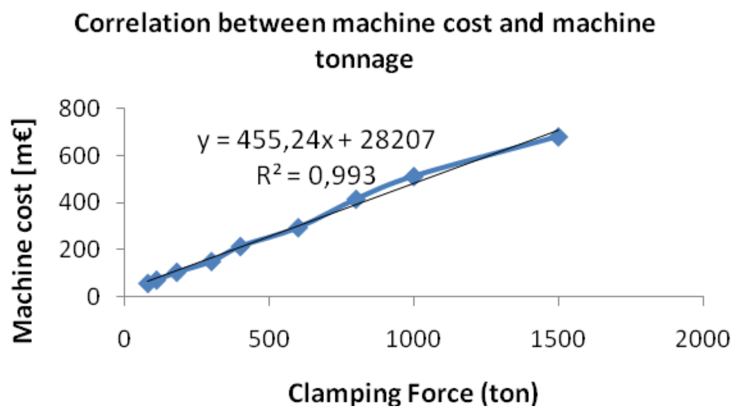

Figure 3. Example of data-based relation. Injection machine acquisition cost is highly correlated to the clamping force.

Finally, if no physical relation is possible and no data is available, like in the mould maintenance case where statistical valid samples are difficult or even impossible to obtain due to the complexity and uniqueness of each mould, empirical relations based on tacit knowledge are a possible solution to estimate future costs. Regarding the injection moulding process, the downtime resulting from mould maintenance issues is an important aspect, as it affects several cost drivers, specially the machine use cost. It is dependent not only on the mould reliability and maintainability, but also on the injected material, on the part complexity and even on the operational maintenance level. Even though there is no adequate data regarding the mould maintenance, the mould designers and users have an experience-based capability to assess these aspects. By conducting structured interviews to industry experts in mould maintenance, it is possible to assess the critical aspects affecting downtime, namely the part geometric complexity, part material abrasiveness and critical mould features (existence of thin mould inserts). This knowledge allows drawing correlations between the expected downtime and the operational maintenance level. Notice, however, that the results obtained in one company with a specific type of moulds/parts may not be valid in other companies.
In this study these relations between the downtime and the maintenance level were defined for all possible combinations of critical aspects. Figure 4 gives an example of the relations obtained for two different combinations.

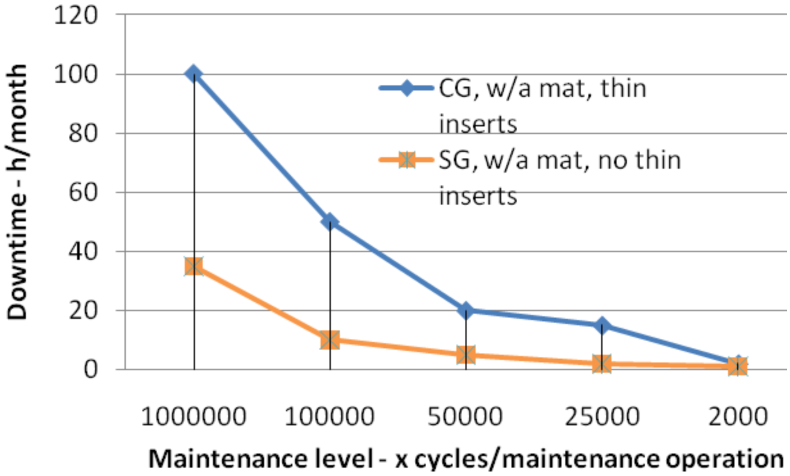

Figure 4. Example of an empirical relation. The downtime is highly dependent on the mean number of injection cycles between maintenance.

2.4 Subjective Life Cycle Cost

In an industrial context, the decisions taken during the design of a mould are not fully captured by the tangible costs. That is, some aspects regarding the mould are weighted differently and their importance is also differently perceived by the different stakeholders. For example, the reliability of a mould affects the required maintenance and the machine downtime in terms of tangible costs, but the machine downtime introduces unevenness in the shop floor, which affects the delivery time and the global production schedule and turns production control into a hard problem. These implications are often more valued by the mould user than the directly perceived on costs. Other variables affecting the production time, as the injection cycle time or the initial investment in moulds, have also an intangible value not truly perceived in costs. In order to capture the importance of these performance aspects to the different stakeholders, a three step method is proposed:

- Identification of the major aspects valued by all the stakeholders.
- Assessment of the importance of these major aspects to the different stakeholders. A questionnaire based on pair-wise comparisons is proposed, which provides a quantification of the importance of the performance aspects to each stakeholder (Subjective Life Cycle Cost).
- Application of the importance weights gathered from the pair-wised comparison questionnaire to the design alternatives. It allows the evaluation of the differences between the best option regarding the conventional Life Cycle Cost and the best option regarding the Subjective Life Cycle Cost.

3 CASE STUDY – FOUR MOULD ALTERNATIVES TO PRODUCE A SMALL, COMPLEX PART

In order to exemplify the methodology described above, a case study was developed during an internship in a company specialized in producing technically complex parts made of polymeric materials, Celoplás. Besides producing the parts Celoplás produces also the required precision moulds for their own use, meaning that the company is simultaneously the mould producer and the mould user. The part chosen for this case study is a connector for the electronic industry. Table 1 presents the main part characteristics relevant to the study.

Table 1 – Part characteristics

Part	Connector
Material	PBT
Part volume	3,73 cm^3
Projected area	279 mm^2
Max thickness	3 mm
Runner diameter	6 mm
Material recycle rate (Max)	30%
Complexity	High

3.1 Mould Cost

As previously explained, different design alternatives are possible to produce a specific part. In this case, four mould alternatives were defined, based on different mould architectures and runner system. The number of cavities was fixed and set to 8. The cost of each mould alternative was computed through the process-based cost models. Table 2 presents the production cost for each alternative. The main cost drivers are labour, machine use and standard mould components. This is explained by the fact that mould production is a time consuming activity, which demands qualified labour and capital intensive equipments. The high cost of the standard components, which include the elements of the mould structure and the runners system, is explained by the strategy of the company of taking advantage of the best standard solutions existent in the market and concentrating on what is really the mould dedicated engineering solution. Differences in cost are considerable, with a 15% cost difference between the lowest cost mould (Mould 3) and the highest cost one (Mould 1). If the decision for the best alternative was made based only on the mould production cost (an indicator for its price), the favoured option would be the mould with the cold runner system (Mould 3). However, that decision would not take into account its performance in the injection moulding process, i.e. during its operational phase. In fact, it is known that the cold runners increase the cycle time, the energy consumption and the material waste in the part injection process. So, only a simultaneous analysis of the mould production and mould usage performance is able to provide the framework for an informed decision.

Table 2 – Production cost of the alternative mould

Mould alternatives	Characteristics	Production cost
Mould1	Inserts per cavity, hot runners, 4 nozzles	58.389 €
Mould 2	Machined in block, hot runners, 4 nozzles	57.477 €
Mould 3	Inserts per cavity, cold runners	50.310 €
Mould 4	Inserts per cavity, hot runners, 2 nozzles	56.289 €

3.2 Life Cycle Cost

The second phase of the methodology is the evaluation of the injection moulding costs for each alternative mould. The integration of both process-based cost models is carried out linking the output and the input of the mould production and injection moulding models, respectively. The mould specifications and the mould cost calculated in the first model affect the cycle time, material consumption, maintenance level and injection machine downtime, which are calculated in the second model in order to reach the part cost. The best mould alternative is the one that results in the lowest cost per final part, but this value also depends on the production volumes. Figure 5 presents the part costs achieved with different moulds for a range of annual production volumes.

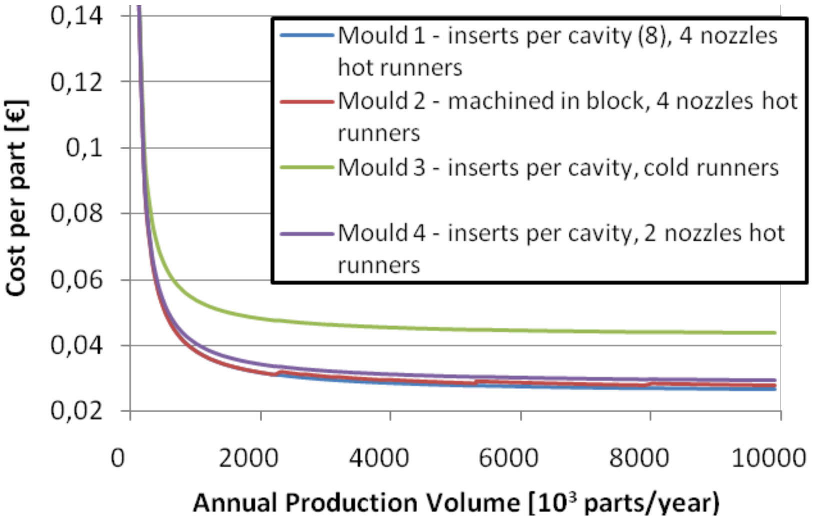

Figure 5 – Part production cost for different production volumes

Except for extremely small production volumes, the lower performance mould in terms of cycle time and scrap percentage during injection (mould 3) is the worst choice in economic terms, despite exhibiting the lowest production cost (Table 2).The other mould options are more similar in terms of cost per part. However, analysing a smaller range of annual production volumes, close to the expected volume (6500000 parts/year), revealed that the lowest cost per part is obtained with Mould 1 (Figure 6), which has the highest production cost. Notice that Mould 2, in which all the moulding cavities are machined in an integral steel block, leads to higher costs if a major repair is required, because the whole block needs to be removed and repaired. In the other moulds, the moulding cavities are made of separate steel inserts, allowing their individual repair. The higher cost of major repairs explains the cost "jumps" when certain annual production volumes are considered.

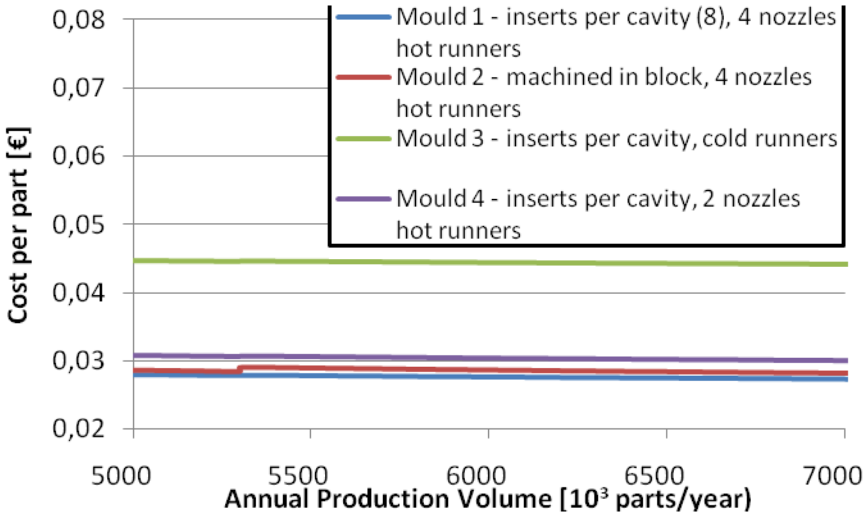

Figure 6 – Part production cost for a smaller range of production volumes (near to the expected one)

It is also interesting to note that if the main cost drivers in mould production are labour, machines use and standard components acquisition, in the injection moulding phase the cost of producing the expected market demand (Table 1) is mainly driven by raw materials, machine use, energy consumption and tooling (Figure 7). The major replacements of the moulding integral block or individual inserts, depending on the mould architecture, are included in the tooling cost and not in the maintenance cost. Maintenance costs regard the preventive and small corrective maintenance operations considering the maintenance level selected for this type of mould and part – in this case, according to the company decision, one maintenance operation per 25000 injection cycles, which means one maintenance every 200000 final parts. This maintenance level considering this mould and part typology is associated with a level of downtime of 15 hours/month, as explained in section 2.3. (Figure 4).

Notice that in order to validate the results obtained with the proposed methodology they were compared with the real costs of the mould produced by the company (Mould 1). The results of the other alternatives were presented and deeply discussed with the company experts, which in an empirical basis validated the results achieved. Moreover, other parts were studied in the same company involving different mould design alternatives to consolidate the proposed approach and validate the results.

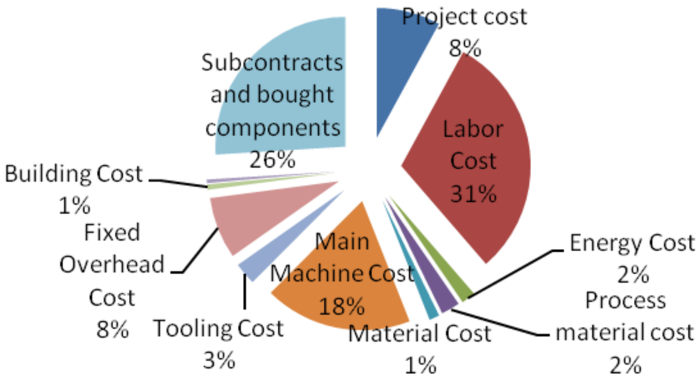

Figure 7 – Cost distribution for Mould 1

3.3 Subjective LCC

The last phase aims to better understand decisions in an industrial context. This was achieved by questioning the different stakeholders involved in different phases of the mould life, in order to identify which aspects are considered as most valuable in a mould. In this industrial context, the critical aspects were mould cost, part production downtime, injection cycle time and mould maintenance cost. Having defined the critical aspects, a pair-wise comparison was performed involving the individual stakeholders. As shown in Table 3, the weights given by each participant are very different. The mould cost is disregarded by the maintenance supervisor, the cycle time disregarded by the supervisor of the mould production and finally the cycle time and maintenance costs are considered as less important by the client manager. Finally, these weights are applied to the normalized results of the previous LCC evaluation (Table 4) to obtain different scores for each mould alternative. As shown in Table 5, the alternatives with high mould cost and low cost per part (Mould 1 and 4 have very similar subjective LCC scores) are preferred by the mould maintenance supervisor. In fact he overlooks the mould cost and emphasizes the mould performance, especially the cycle time and downtime. Finally, the other stakeholders prefer the lower cost mould alternative, although for this production volume it incurs in higher part costs (higher life cycle costs). This can be explained by a higher focus on mould cost and by the disregard for the cycle time. If it is understandable for the mould production supervisor (mould cycle time is not perceived as "his business"), it is more surprising for the client manager. However, for the client manager the critical features are a smooth and reliable work flow by having a reduced downtime and low investment in the mould, whereas small cycle time differences are manageable.

It should be noted that none of the stakeholders identified the material waste as an important aspect for the mould. However, the alternatives under study generate different material waste quantities and, in a considerably small part variable, this waste can be significant for the decision. To understand the reasons for the non-inclusion of material waste as an important aspect of the mould is the next step of the study, because it will modify the selection of the best alternative.

Table 3 – Pair-wise analysis results

	Mould Cost	Down-time	Cycle Time	Maintenance
Mould production supervisor	36%	44%	2%	18%
Maintenance supervisor	2%	30%	45%	23%
Client manager	27%	62%	9%	2%

Table 4 – Absolute and normalized scores of the alternative moulds in each criteria

	Mould cost [€]		Downtime [hrs per day]		Cycle time [seconds per part]		Maintenance Cost [€]	
	Absolute value	Normalized value	Absolute value	Normalized value	Absolute value	Normalized value	Absolute value	Normalized value
Mould 1	58389	-1,05	0.54	0.00	4.51	0,67	4127	0,67
Mould 2	57477	-0,70	0.54	0.00	4.51	0,67	32777	-2,00
Mould 3	50310	2,00	0.54	0.00	5.50	-2,00	4127	0,67
Mould 4	56289	-0,25	0.54	0.00	4.51	0,67	4127	0,67

Table 5 - Subjective LCC results

	Mould production supervisor	Maintenance supervisor	Client (mould user) manager
Mould 1	-0,24	0,43	-0,21
Mould 2	-0,60	-0,17	-0,17
Mould 3	0,80	-0,71	0,37
Mould 4	0,04	0,45	0,01

4 SUMMARY

In this paper a life cycle approach to support design decisions of dedicated moulds is proposed. Aiming to support early design decision making, it integrates engineering knowledge with management tools in order to estimate the impact of alternative mould designs throughout their life cycle. By understanding the life cycle effects of a dedicated mould it is possible to decide more consciously about alternative design solutions. As showed in the case studies, the lower cost alternative may lead to the higher part cost. Moreover, the costs throughout the life cycle of a mould are differently perceived by the different stakeholders involved in distinct life time stages.

The model developed aims to capture all these aspects. The development of mould production and injection moulding cost models allows the direct correlation between injection moulding parameters and tool design decisions. By using data fitting and tactical relations to correlate critical mould design features and injection parameters (usage phase performance), it is possible to convert different engineering mould design solutions into tangible costs that take into account both the mould production and the mould usage phase. Finally, the last part of the model captures the importance given by different stakeholders in the tool life cycle to different cost drivers.

In order to illustrate the model a case study was presented regarding four alternative injection moulds with considerably different production costs, but able to produce the same part within the required specifications. The results showed that for the expected annual production volume of the company, the economically best alternative was the higher cost model – illustrating therefore the need for a comprehensive life cycle analysis to support informed mould design decisions. Moreover, the analysis of the subjective LCC revealed that different stakeholders have different preferences in mould choices, depending on their responsibility within the value chain. Having this methodology been applied in one company, future work will comprise the analysis of other case studies in other organizations to both further validate the methodology and to assess good practices in mould design.

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