Development of models for operationalisation of eco-efficiency indicators: Application to mould design and plastic injection processes

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Abstract

Following society's growing awareness about environmental aspects, the importance of implementing environmental philosophies within companies is undeniable. Eco-efficiency serves as a bridge between economy and environment relating, through eco-efficiency ratios, the value of the product/service with its environmental impact, trying to maximise product value and minimise the associated environmental impact. The present dissertation has as goal of making eco-efficiency philosophy operational through the development of simplified models for the calculation of indicators of eco-efficiency, hoping that the existence of simplified models contributes for a more generalise use of eco-efficiency within corporate sphere. With the intent of making this work's area of action broader, three different scenarios within the production process of mould and plastic injection companies were identified and for each one of them a simplified model that estimates economic, environmental and eco-efficiency results was developed. The results are presented in the form of comparison between the three models developed and offer analysis for different types of plastic materials, and for a different number of cavities. The analysis performed over the results allowed to reach some conclusions about the capacity of models to act with precision in the industry and about similarities and differences between them.
Keywords: Eco-efficiency, Simplified models, Plastic injection, Mould design, operationalisation

1. Introduction

Since the beginning of the industrial era, the corporate sphere has had an immense impact on the environment. In the 20th century, environmental movements started pointing out that there were environmental costs associated with the manufacturing industries and in at the end of the century, environmental problems became global in scale. An increasing global awareness of the threat posed by ignoring environmental impacts gave birth to a new paradigm, which brought to centre stage the pursuit of a common ideal. In the industrial field, this new paradigm brought the appearance of a new philosophy where not only economic indicators were used to assess a business model but also environmental indicators.

The first notion of eco-efficiency (EE) can be traced back to AM Freeman III and RH Haveman in the 70s as the concept of "environmental efficiency" [4] but it was in 1992, that the concept of eco-efficiency was widely popularised in Changing Course (Schmidheiny 1992), a publication of the World Business Council for Sustainable Development (WBCSD)[3].

From the several existing definitions of EE, the one provided by WBCSD is often referred in works related to eco-efficiency, and it will be the one used in this work also. According to WBCSD, "eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the Earth's estimated carrying capacity" [17]. Eco-efficiency can be calculated using equation 1 [1].

$$Eco-efficiency = \frac{Production\,or\,service\,value}{Environmental\,Influence} \tag{1}$$

In the business sphere, WBCSD affirms that to become more eco-efficient, a company should focus on well-known methods and strategies and as such, to help companies achieve a better eco-efficiency, proposed seven elements which may lead to improved eco-efficiency in business [17],

[1], [16]. These seven principles are presented in table 1 where they were grouped accordingly with their function.

Table 1: Seven principles of eco-efficiency as stated by WBCSD.

Function of the principle	Eco-efficiency principle
Resource optimization	Reduce material requirements Reduce energy intensity Reduce toxic dispersion
Increase of value	Enhance material recyclability Maximize use of renewable resources
Reduction of environmental impacts	Extend product durability Increase service intensity

It can affirmed that eco-efficiency concept is well-established. Nonetheless, looking at the equation that quantifies eco-efficiency we notice that the concepts of value and environmental are generic and vague, leading to the possibility of different interpretations. Thus the necessity of having appropriate metrics that allow a better orientation is essential [5].

The necessity of quantifying eco-efficiency in order to gather quantitative and qualitative information for making decisions gave birth to EE indicators. Indicators are defined as parameter or reference for a parameter and serve the purpose of assessing the progress of a company [11].

In order to ensure indicators are relevant, accurate and scientifically supportable, WBCSD presented eight characteristics that indicators should have [15]:

(i) "Be relevant and meaningful with respect to protecting the environment and human health and/or improving the quality of life"

(ii) "Inform decision making to improve the performance of the organization"

(iii) "Recognize the inherent diversity of business"

(iv) "Support benchmarking and monitoring over time"

(v) "Be clearly defined, measurable, transparent and verifiable"

(vi) "Be understandable and meaningful to identified stakeholders"

(vii) "Be based on an overall evaluation of a company's operations, products and services, especially focusing on all those areas that are of direct management control"

(viii) "Recognize relevant and meaningful issues related to upstream and downstream aspects of a company's activities"

The WBCSD asserts that the indicators can be classified as Generally Applicable indicators and Business Specific indicators. The Generally Applicable indicators are used by any business or company and use metrics typically accepted such as Eco-Indicator 99 or ReCiPe for environmental impact measurement. Business Specific indicators are defined from one sector to another. In the of the latter, WBCSD recommends the use of the ISO 14031 standard as a guide for the selection of relevant indicators [11].

Eco-efficiency's universality can be proved by the multitude of areas where it has been used. Scientific papers which have eco-efficiency as base can be found in areas like electricity production [6], fruit production [9], steel industry [14], biocomposites [7], logistics networks [10].

The examples described above show that although being an extensive philosophy, eco-efficiency presents a major drawback. Defining eco-efficiency as the ratio between value and environmental impact 1, leads to the necessity of finding these two quantities for any given system. This characterization process can be quite complex due to the necessity of knowing the economic (if the value was defined as such) and environmental impacts of a system in its entire life cycle [13].

This drawback leads to the conclusion that finding a way to turn EE operational, i.e. turn the formulation of EE and its indicators simpler, would be tremendously useful to companies, organisations or any other entity who wishes to apply this philosophy in a regular way.

2. Operationalisation of Eco-Efficiency Models

Although operationalisation and simplification can be interpreted as similar concepts, they carry different meanings in this work.

Operationalisation should be seen as the act of making something practical, of easy usage. On the other hand, the use of simplification should be considered as a mean to reach that operationalisation.

Regarding eco-efficiency, its use carries some difficulties, namely, the elevated number of inputs that feed an eco-efficiency model and the arduous work needed to obtain them. These obstacles, make the use of eco-efficiency non-practical i.e. non-operational for regular use.

This transformation of a non-operational model towards an operational one is the main objective of the dissertation and will be accomplished by simplifying methods.

This idea of simplification of methods will be shown in this dissertation through three different models representing three different scenarios connected to distinct moments of the use of eco-efficiency in mould and injection industries.

2.1. Models basic concepts

Commonly, the group of mould manufacturing and plastic injection industries can be divided into three types:

- **exclusive mould manufacturers** - This kind of situation refers to those companies that solely manufacture moulds for the injection industry. In this type of companies, the plastic injection processes are non-existent.
- **exclusive plastic injection manufacturers** - This kind of situation refers to those companies that solely act on the plastic injection process. In this type of companies, the mould is acquired from a third party. Mould manufacturing is non-existent.
- **hybrid manufacturers** - This kind of situation refers to a mix of the previous two types. In this type of company the majority of the processes are exercised "indoors", from the mould creation to the final piece obtained from plastic injection.

Along this work only the two first types of manufacturers will be addressed, due to the fact that the last one - hybrid manufacturers - can be seen as the pairing of the first two entities.

Along with this work, the system in study was defined by a set of phases, namely, "Project development", "Negotiation phase", "Start of mould production", "End of mould production", "Start of injection process", and finally "end of injection process".

2.2. Exclusive model objectives

Although the models have the same main objective, they differ from each other because each one of them represents a different scenario. Due to this difference, a new set of objectives arises, objectives that intend to represent the necessities that each scenario presents. Due to this exclusivity of the models regarding some objectives and in order to differentiate them from the main one, it was settled that these set of objectives will be known as exclusive model objectives. These objectives can be divided into primary and secondary EMOs. While the primary EMO must be fulfilled to achieve the main goal, the secondary does not, its fulfilment serves mainly to improve the precision of the model.

2.3. Type of inputs

The inputs that feed the model were divided into two groups: active inputs and inactive inputs. Active inputs are those that must be loaded by the user every time the model is used giving some degree of freedom to the user.

Inactive inputs are fixed (constant value) inputs. These must be loaded previously to the use of the model and are used together with active inputs to predict results. Loading the models with inactive inputs can be a time-consuming task, but has the advantage of only being done the first time the model is used or when something major changes in the manufacturing company.

3. Operationalisation Model - Process Selection Model

The first model developed arises from the necessity of having real-time data that would serve as a base to make process decisions allowing the educated choices about what path to take to achieve the desired results.

Although the model acts in both exclusive mould manufacturers and exclusive plastic injection manufacturers its role differs depending on the type of manufacturer.

For exclusive mould manufacturers, it can be noted that using the model at "Start of Mould Production" gives the manufacturer data that allows selecting the better path for the manufacturing of the mould and using the model in "Star of Injection Process" provides data about injection process. The usefulness of such data for exclusive mould manufacturers is diverse. It can be seen as adding value to the service provided if we consider that this data can be delivered to clients with the mould.

For exclusive plastic injection manufacturers, the model is able to provide an estimation or more precise data about the injection process if estimation inputs or real ones are used (obtain from a post production stage), respectively.

Using the same model at the end of production, feeding it with real results instead of predicted ones, gives more precise results and therefore can be used to study the processes and gather relevant data to improve the model and future choices.

The capabilities described in the last paragraphs can be translated into EMO. The primary EMO is the capability of predicting economic, energetic and eco-efficiency indicators for the moulds to be manufactured and for the plastic injection process. The secondary EMO is the ability to feed a database of characteristics of the processes. This allows a better understanding of the processes by comparing the manufactured mould and plastic piece's process characteristics with others previously made, giving the model a continuous improvement capability.

Thus, it can be concluded that, and in consequence of the definition of primary and secondary EMO, the completion of the primary EMO is mandatory to achieve the objective of the thesis, while the completion of the secondary EMO is optional. The secondary EMO allows the user to store the results of every mould a plastic piece produced allowing a better understanding of the processes by comparing the manufactured mould's characteristics with others previously made, it provides the model with a continuous improvement capability.

One of the main differences between these two exclusive model objectives resides at the different time stage where they act. While the secondary one, in order to fulfil the requirement of creating a database, demands input values with minor errors and therefore known values, which can be obtained in a post-production stage, the first one doesn't do it so. In order to fulfil this primary objective, predictions about process characteristics can be seen as acceptable inputs. Table 2 resumes the model's characteristics.

Table 2: First model's targets and approach

Who	When	Why	How
Mould manufacturers	Start of mould production	Process selection by results prediction	Feeding the model with predicted inputs
	End of mould production	Process study	Feeding the model with exact inputs
	Start of injection process	Add value to service	Feeding the model with predicted inputs & providing the clients with predicted results
Plastic injection manufacturers	Start of injection process	Results prediction	Feeding the model with predicted inputs
	End of injection process	Process study	Feeding the model with exact inputs

3.1. Model 1's Methodology

The development of the model started by identifying an existing situation in the industry, regarding eco-efficiency, that could be improved. Following up, the specific exclusive model objectives were identified and thus, the area and time of operation is identified. Having defined the area of operation of the model, its core development started by dividing the process into two production areas: mould production and plastic injection process. For each group a stage break-down was made and the sub-processes that are part of them were identified. As the sub-processes were defined, the identification of the variables that compose those sub-processes was done and those were related to each other through a series of equations.

In the mould manufacturing model, figure 1 identifies the cost groups and subgroups identified.

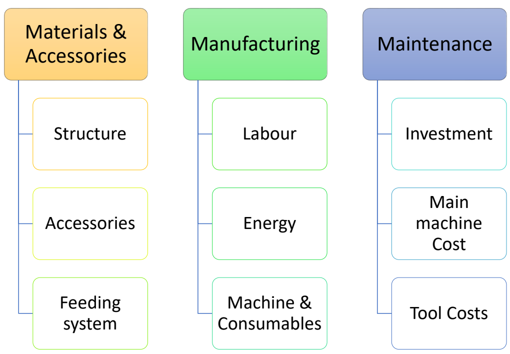


Figure 1: Economic model major groups overview

To simplify the model, the inputs needed to fill the equations found were turned, when possible, to inactive inputs using empirical data and, those parameters with low cost or environmental impacts, were neglected. The way to transform active inputs into inactive inputs is offered together with suggestions about pre-fixed values for them, accordingly to empirical data. For the injection p process a similar approach was taken. The costs can be divided into several categories: material, labour, energy, machine cost,tool cost and maintenance costs.

4. Operationalisation Model - Negotiation phase

The second model follows the macro objective of this dissertation, i.e, to provide a operational method to the use of indicators of eco-efficiency by means of simplification of calculations and approaches, but it also has its own exclusive model objectives. These EMO were divided into two sets. The first and primary EMO is to provide estimations of results (once again, economic and environmental) giving negotiation flexibility to the manufacturers. The secondary EMO has a pedagogic aspect. By continuously dealing with costumers manufacturers will possibly learn costumers' common wishes. Learning what costumers generally want will provide information that can be used to improve the model.

One practical example of the secondary EMO is the manufacturers understanding of the desire of a new plastic material after several costumers inquire about the cost of making their product in this hypothetical material. With this new information, the model can be updated with data of this desired material.

From the primary EMO - to predict results in both economic and environmental spectres, obtaining at the same time negotiation flexibility - should result a set of data destined to the manufacturers. The data derived from the model, when this one's used with the primary EMO in mind, should provide the manufacturers real-time weighted economic and environmental results, so they can be used to achieve greater flexibility in the negotiation aspect.

From the secondary EMO - obtaining information about what costumers want - the data resulting from its use is destined to both manufacturers and costumer. The manufacturers benefit from this information by updating the model being used with new aspects. This is especially useful for example in the exploration of a new foreign market where what is assumed as common sense might not be so at the new market.

On the other hand, clients benefit from this by results related to what the costumer really wants.

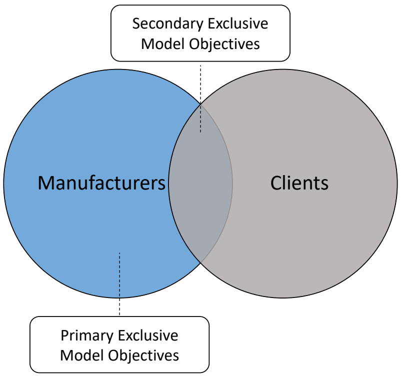


Figure 2: Exclusive objectives targets

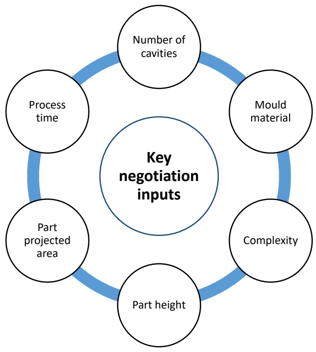


Figure 3: Desirable key inputs for negotiation meetings - mould manufacturers

Unlike the previous model where the exclusive model objectives acted in different time stages, in this model the EMO act at the same place in time - Negotiation phase. A summary of the model's target is presented in the table 3.

Table 3: Second model's applicable universe

Who	When	Why	How
Mould manufacturers & Plastic injecction manufacturers	Negotiation phase	Results prediction	Feeding the model with predicted inputs
		Add value to service	Feeding the model with predicted inputs & Providing the clients with predicted results
		Clients characterization	Learning what clients in general want & Updating the model with those requirements

4.1. Model 2's Methodology

The first step of the model's development is identifying an existing problem in the industry regarding the use of eco-efficiency. The next step is to define the area and time of operation. After the goals are defined, the development of the model begins with the division of the process into two production areas: mould and injection process. For each group, the identification of a set of characteristics (active inputs) essential to a negotiation phase is done by interviewing people from the industry. Following the previous step, a breakdown of the groups is done. As the sub-processes are identified, the recognition of the variables that compose those sub-processes is done. The group breakdown and the type of simplifications are similar to model 1. Figures 3 and 4 show the active inputs for mould manufacturing and injection.

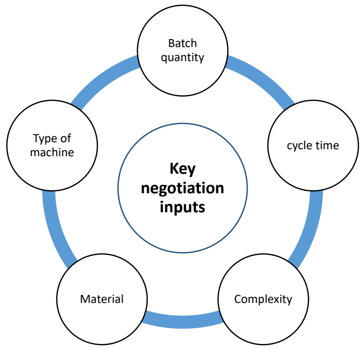


Figure 4: Desirable key inputs for negotiation meetings - plastic injection manufacturers

5. Operationalisation Model - Early Design

Similarly to model 1 and model 2, this third model follows two major groups of objectives, the macro objective and the exclusive model objectives.

Unlike the previous two models where a couple of exclusive objectives were identified, model 3 is characterized by only a single EMO. This EMO has the goal of providing estimations of economic and environmental results in a very early stage of the manufacturing process. At this phase of the manufacturing process, the plan for production is not defined or isn't important. This lack of certainty in the production process results in a model where the specific capabilities of the manufacturing company are not taken in consideration, in other words, the existing assets in a certain company do not influence the results given by the model, these come from empirical data stemming from diverse sources.

This early design model finds its target audience in those in the general public/clients who want a cost estimative from just few aspects of the plastic part in mind, such as piece geometry and batch, and in agents connected to manufacturing industries, like designers, who require estimates to choose a better path for their design.

For the first group - clients - the production process is not important since the what's important is the final result and not the path to achieve it. For the second group - designers - at an early stage, the manufacturing process is not developed yet so precise characteristics about production means are unknown.

Figure 5, shown below, points the existing differences within the target groups of the model.

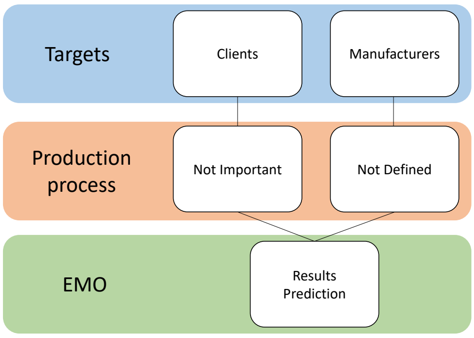


Figure 5: Early Design Model - Targets characteristics and EMO

The intention of the third model is to provide an early view of the expected economic and environmental results to not only all types of industrial schemes presented before - mould manufacturers and plastic injection manufacturers - but also to potential clients.

Regarding the first type of manufacturing schemes named above - mould manufacturers - the model is directed only to mould production, providing an early estimative of results.

For exclusive plastic injection the utility relies on the same explanation from above, except the results are directed to the production of plastic object.

For the potential clients, the model delivers the same type of results described above, providing its user with an idea of what to expect. A summary of the target company and is presented in table 4:

Table 4: Third model's applicable universe

Who	When	Why	How
Mould manufacturers designers	Project development phase	Mould results predictions	Feeding the system with empirical data
Injection manufacturers designers	Project development phase	Injection results predictions	Feeding the system with empirical data
Clients	Project development phase	Mould & Injection Results	Feeding the system with empirical data

5.1. Model 3's Methodology

The development of the model starts by identifying an existing situation in the industry, regarding eco-efficiency, that could be improved. Following up, the specific exclusive model objectives are identified and thus, the area and time of operation are known. Having defined the area of operation of the model, its core development starts by dividing the process into two production areas: mould production and plastic injection process.

Starting with the mould production phase, subgroups that compose the mould manufacturing were identified (figure 6) and a set of general equations from literature were selected and used together with empirical data collected directly in a mould company. It should be noted that the model created is based around few characteristics from the part being manufactured: dimensions and batch, since these are the only known parameters at this temporal stage.

The same method was used for injection and, in this case, the subgroups identified are shown in figure 7.

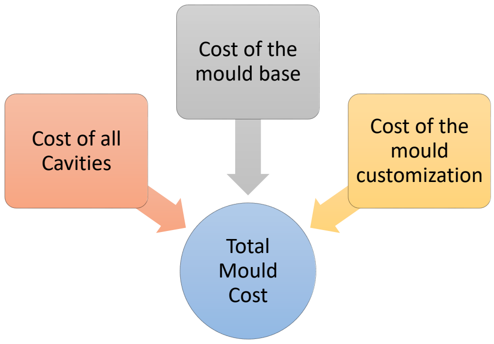


Figure 6: Cost groups identified for the mould maufacturing

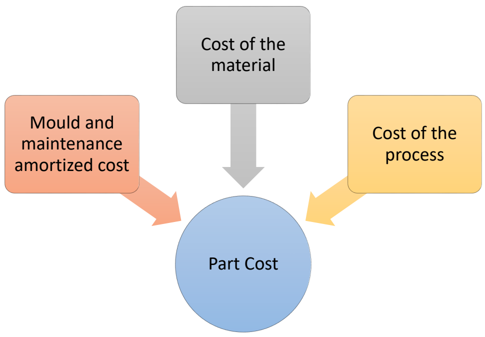


Figure 7: Cost groups identified for the injection process

6. Environmental Models

It was decided that although the economic models were included in each individual model's chapter, the environmental part would be put together in this chapter. The reason behind this decision falls on the fact that the environmental models' differences between each scenario are few and, therefore, it will be easier to make a first comparative analysis this way. To do the environmental analysis the ReCiPe method [8] was used. To obtained the weights SimaPro software was used and weighted parameters were gathered from previous works [12][2].

Starting with the impacts related to the mould manufacture, the first step is the identification of the parameters that generate environmental impacts. These are: the material required to fabricate the mould, the amount of recycled material withdrawn during procedures, the consumables used by the machines during operations and the energy consumed for each machine.

The first simplification applied in every model is the assumption that the mould is made of a generic stainless steel thus, for environmental data an average value for steel is used. A similar approach was taken regarding the consumables, which were divided into three types: oils for machining processes except EDM and specific oils for EDM processes.

The global environmental impact is given by equation (2):

$$EI = \sum_{1}^{i} Material \cdot EI_i + \sum_{1}^{i} Recycledmaterial \cdot EI_i + Consumables_i \cdot EI_i + Energy_i \cdot EI_i \quad (2)$$

For the injection moulding process the resources that influence the environment are: the material injected, the wasted material, the environmental impact of the mould and the energy consumption.

The global environmental impact for injection is given by equation (3):

$$EI = \sum_{1}^{i} Material \cdot EI_i + \sum_{1}^{i} Recycledmaterial \cdot EI_i + Mould + Energy_i \cdot EI_i \quad (3)$$

7. Results

The results offered in this chapter are divided into four sections: Assessment on simplification, mould production results, injection results and eco-efficiency results.

7.1. Assessment on simplification

In this section, an assessment on simplification is made. To make this, a comparison between the number of inputs is offered in figures 8 and 9 since these can be used as indicators of simplicity.

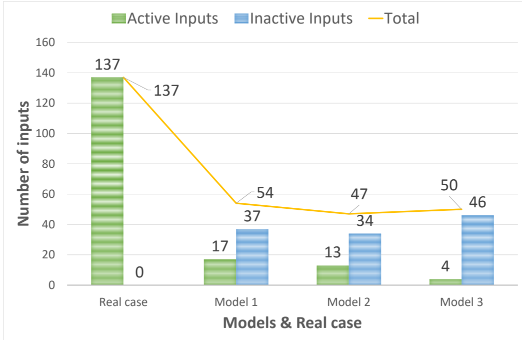


Figure 8: Mould - Inputs overview

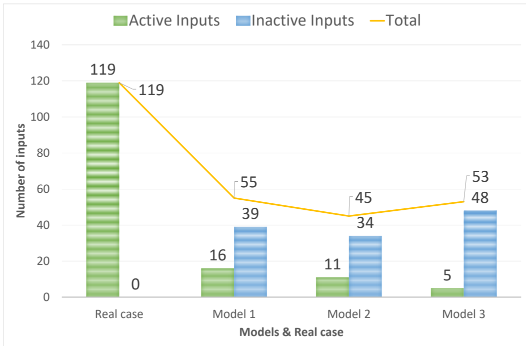
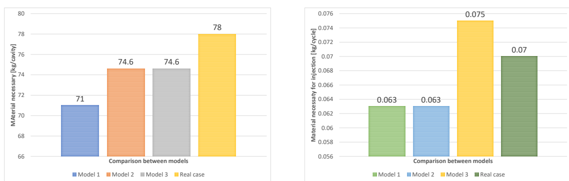


Figure 9: Injection process - Inputs overview

In every case, there was a reduction of the number of inputs necessary to construct the model and the majority of these were turned into inactive inputs. These two facts lead to the conclusion that simplification was achieved. The trade-off between this achieved simplicity and precision is addressed in the next sections.

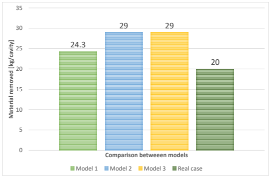
7.2. Resources Inventory

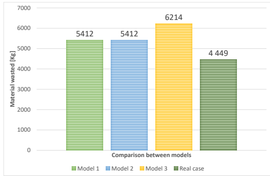
Figures 10 and 11 show the material necessary and the material removed and wasted respectively.



(a) Mould manufacturing **(b)** Injection process

Figure 10: Material need for production





(a) Mould manufacturing **(b)** Injection process

Figure 11: Material removed and wasted in production

In terms of material needed there's no difference between model 2 and 3 since they use the same approach to predict it.In the injection process, model 1 and model 2 present the same results since they use same equations to predict material needed. Regarding the material removed, the quantity of material removed for the mould in models 2 and 3 is the same since they use the same methodology to predict this value.

The material wasted during the injection process is the material used during the maintenance interventions and the material that represents the rejected parts. Model 1 and 2 predict the wasted material the same way, thus they offer the same result. Fig. 12 shows the energy required for the mould and tab.5 for injection and depends on the macine's clamp force.

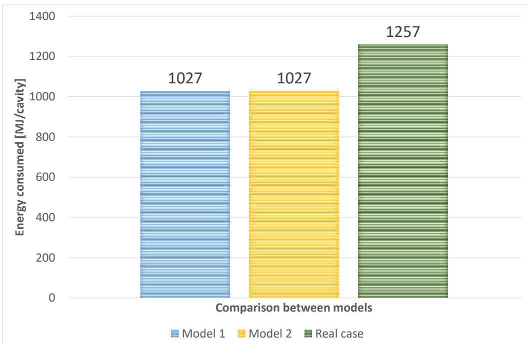


Figure 12: Energy consumed in the production of the mould per cavity

Table 5: Energy consumed per machine

	Electrical machines	Hydraulic Machines
Clampage	Consumpion [MJ]	
[0-60]	635 254	825 830
]60-120]	698 475	908 017
]120-180]	729 584	948 459
]180-240]	795 475	1 034 117

Regarding the energy consumption, it depends on the machine and therefore, on the choice of the user. In the mould production model, 1 and 2 use the same equations to predict energy. Model 3 does not offer energy estimation directly, therefore the value used in the other models is adopted.

In injection, the energy depends on the clampage and material and corresponds to 635 254[MJ] a value 16% higher than the real one. This difference can be justified by the difficulty that is to predict energetic values. To predict the energy for model 3, an average value for the intervals shown above is taken.

8. Mould Results

Costs and environmental results are presented in tables 6, 7 and 8

Table 6: Mould cost by group - model 1, model 2 and real case

Individual Cost [K€]	Model 1	%	Model 2	%	Real Case	%
Labour	9.2	8.8	10.3	9.05	8.83	7.69
Energy	0.63	0.60	0.63	0.55	0.34	0.29
Consumables	0.2	0.19	0.2	0.17	0.13	0.11
Material	90.05	80.4	87.24	81.04	96.61	84.2
Machine	9.54	9.12	9.54	8.38	7.18	6.25
Tooling	0.80	0.76	0.80	0.70	1.50	1.3
Maintenance	0.11	0.10	0.11	0.10	0.18	0.15
Total[K]	110.53	100	108.82	100	116.77	100
Total per cavity [K€]	6.9		6.80		7.30	

Although there's a difference between the predicted costs and real model cost, the principal cost driver is the same for both models and real case - material.

Table 7: Model 3 cost estimates per cost group

Cost Group	Modelo 3	
Mould Base	47.06	
Cavities	28.33	
Customization	62.5	
	Modelo 3	**RealCase**
Total [K€]	137.89	116.77
Total per cavity [K€]	7.99	7.30

There is a difference of cost between model 3 and the real case of 19% making model 3 the model with the worst precision. This high percentage is expected since model 3 must assume a great number of simplifications.

Table 8: Environmental Impacts (EI) results to produce mould A

[Pts]	Modelo 1	%	Modelo 2	%	Modelo 3	%	Real Case	%
Material Necessary	1807.376	87.7	1899.0176	88.69	1899.0176	89.12	1985.57	87.37
Material Removed	-58.32	2.83	-69.6	3.25	-69.6	3.27	-48	2.11
Consumables	223.4	10.84	223.4	10.43	213.14	10.0	227.12	9.99
Energy	88.24	4.28	88.24	4.12	88.24	4.14	108	4.75
Total	2060.70	100	2141.058	100	2130.80	100	2272.69	100
Environmental Impact per cavity produced								
	Modelo 1		**Modelo 2**		**Modelo 3**		**Real Case**	
Total [Pts]	128.79		133.816		133.175		142.04	

Environmental impact is mostly influenced by the material required to produce the mould, followed by the consumables impacts and then the energy impacts.

9. Injection Results

Costs and environmental results are presented in tables 9, 10 and 11.

Table 9: Comparison between models for the injection individual costs using an electrical machine

Individual Costs [K€]	Model 1	%	Model 2	%	Real Case	%
Material	601.12	78.93	598.32	78.86	618.66	78.18
Energy	8.07	1.06	8.07	1.06	9.16	1.15
Labour	46.85	6.15	46.85	6.17	48.90	6.17
Machine	32.30	4.24	32.30	4.26	35.59	4.49
Tooling	72.22	9.48	72.22	9.52	75.53	9.54
Maintenance	0.98	0.13	0.98	0.12	0.74	0.09
Total [K€]	761.54	100	758.74	100	791.32	100
Total per cavity [K€]	47.60		47.42		49.46	

The primary cost driver in the injection process is the cost of the material with almost 80% of the total cost, in every model including the real case.

Table 10: Comparison between real cost and cost predicted by model 3 for injection moulding

Cost Group [K€]	Modelo 3	
Amortized Cost/yield	102.21	
Material Cost/yield	538.03	
Processing Cost/yield	51.10	
	Modelo 3	Real Case
Total [K€]	691.34	791.32
Total per cavity [K€]	43.21	49.46

Once again it's model 3's results that diverge further away from the real case results. In this case, the cost predicted corresponds to 87.36% of the real case cost. But once again it is in the material group that the largest portion of the cost happens.

Table 11: Comparison between the models' environmental impacts estimations for injection

[Pts]	Modelo 1	%	Modelo 2	%	Modelo 3	%	Real Case	%
Injected Material	106 214.2	90.61	106 214.2	90.48	110 458.64	90.34	108 342.48	90.01
Recycled Material	-1 214.45	1.04	-1 214.45	1.03	-1 398.45	1.14	-1 009.97	0.84
Energy	8101.64	6.91	8101.64	6.90	8 954.87	7.32	8 502.58	7.06
Mould	4121.42	3.52	4282.11	3.65	4261.6	3.49	4 545.38	3.76
Total [Pts]	117 222.81	100	117 383.50	100	122 276.66	100	120 359.70	100

The material used for the injection process is the most powerful impact driver in every model, including in the real case. This aspect is expected due to the high quantity of parts being produced. Model 1 and model 2 present similar results since they often use the same equations.

10. Eco-efficiency Results

The value part of eco-efficiency is given by equations (4) and (5) for mould and part respectively:

$$Mould's\,Profit = Sales - Material\,C. - Energy\,C. \\ - Labour\,C. - Machine\,C. \quad (4)$$

$$Part's\,Profit = Sales - Material\,C. \\ - Energy\,C. - Labour\,C. \\ - Mould\,C. - Machine\,C. \quad (5)$$

The sales,accordingly to the company's strategy, correspond to a value of 20% over the part's production cost.

Regarding the impact part for EE ratio, it's used mould impact and part impact. Eco-efficiency results for mould and injection are shown it tables 12 and 13.

Table 12: Mould's Eco-efficiency indicator for the models developed and real case

	Model 1	Model 2	Model 3	Real Case
Value Indicator [K€]	23.22	22.9	25.31	26.954
Mould EI [Pts]	2060.70	2141.058	2130.80	2272.69
EE ratio [€/Pts]	11.27	10.70	11.89	11.86
EE relative error	-0.049	-0.097	+0.002	0.00

The predicted results for the value indicator are similar between models, corresponding to 86.1%, 84.9% and 93.9% for model 1, model 2 and model 3 respectively. Concerning the eco-efficiency ratio, EI_{mould}, interestingly model 3 presents the least error (0.2% above the real value).

Table 13: Injection process Eco-efficiency indicator for the models developed and real case

	Model 1	Model 2	Model 3	Real Case
Value Indicator [K€]	153.288	142.24	138.26	161.74
Mould EI [Pts]	117 222.81	117 383.50	122 276.66	120 359.70
EE ratio [€/Pts]	1.31×10^{-3}	1.21×10^{-3}	1.13×10^{-3}	1.34×10^{-3}
EE relative error	-0.022	-0.097	-0.16	0.00

With respect to the eco-efficiency ratio, EI_{part}, unlike the EI results obtained for mould production, model 3 presents the least accurate results, having predicted this ratio with 16% difference in relation to the real case. This fact is explained mainly due to the difference in costs between model 3 and the real case (13.64%). Model 1 presents a relative error of 2.2% regarding the real case and in model 2 this error figures among 9.7%.

11. Conclusions

This work had the goal of creating three simplified models that contributed for the operationalisation of eco-efficiency in the mould and injection moulding industries. To understand how the industry works and to gather the necessary data several visits to industry were made.

Simplifications were made by transforming active inputs into inactive ones. To do this a study of the data gathered from a mould manufacturing and injection moulding company was used, together with research made in books and scientific papers, catalogues and previous works.

Some simplifications, like energetic parameters and tooling, can be considered rather crude but they are still justifiable by the difficulty and lack of patterns between moulds or parts manufactured.

The models created were validated and respect one of the thesis objective - simplification to achieve operationalisation. Not only the number of inputs were reduced but also the majority of them were turned into inactive inputs, meaning that users can obtain results quickly from few inputs, after composing the model with inactive inputs.

Looking at results we see that model 1 and 2 present similar results. This fact can be explained by the fact that both of the models use same equations. The use of model 2 starts with the identification of primary active inputs necessary to a negotiation scenario, and although model 1 does not make this identification, these same active inputs are used to model the mould manufacturing and injection moulding systems.

This situation can make anyone question if model 1 and model 2 are not interchangeable. In fact, although model 1 was built with a specific scenario in mind, a scenario where negotiation didn't entered, it has the capability of being used at one, and this fact may make model 2 redundant.

Model 3 represents a scenario where the users have the desire of producing a plastic piece and want information about the costs and impacts of that production. Results show that there's a significant difference between results predicted by model 3 and the real results. This gap is expected since there's no information about the manufacturing process and all calculations are based on empirical data. But even with this difference between results, model 3 can be useful as a first approach to costs and impacts.

Having said this, it can be concluded that operationalisation was achieved.

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