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Analytical cost estimation model in High Pressure Die Casting

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Abstract

The present paper aims at the definition of an analytical model for the cost estimation of the High Pressure Die Casting (HPDC) process. The model is based on two main pillars: (i) knowledge formalization and (ii) cost estimation algorithms. The novelty of this approach is the link between the analytical model (algorithms) and the geometrical features of the product under development. The relationship between geometrical features and cost items gives an accurate result in terms of cost breakdown, supporting designers for the application of Design-to-Cost rules in HPDC sector.

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*Keywords:*cost estimation, High Pressure Die Casting, analytical cost model, knowledge formalization.

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1. Introduction

The use of product/process-related data and information throughout the product lifecycle is a key aspect of the Intelligent Manufacturing. During the design phase, designers establish up to 80% of the product cost, even included the manufacturing cost. The process-related information sharing within the enterprise is a solution for improving the manufacturing flexibility. Moreover, the availability of big data from production plants may support designers in

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finding best solutions in terms of feasibility and cost. Analytical manufacturing cost estimation methods and systems, based on the calculation of the manufacturing process, allow designers to get the manufacturing cost of a product by considering accurate scenarios. Among the different methods developed for cost estimation at the design stage, the most used are those ones based on knowledge, features, operations, weight, material, physical relationships and similarity laws. The paper aims to define a structured analytical model for the cost estimation of High Pressure Die Casted (HPDC) components. HPDC is a casting process characterized by forcing molten metal under high pressure into a die cavity. The method is based on two main pillars: (i) knowledge formalization and (ii) cost estimation algorithms. The first pillar is the exact characterization and classification of cost items involved in the HPDC process including the knowledge collection and its formalization (both internal-from companies and explicit-from literature). The second pillar is the definition of algorithms and equations for predicting HPDC manufacturing costs. The relationships between the HPDC cost items and the product attributes (e.g. roughness, maximum thickness, etc.) have been developed for the analytical model definition. By using this model, designers can estimate the cost of a product during the early design stage with the aim to provide the most competitive solution.

The novelty of this approach is the definition of the analytical cost estimation model in the field of the HPDC starting from the geometrical features of the product under development. The relationships between geometrical features and the cost items will give a more accurate result in terms of cost breakdown and it can be used by product designers as a powerful tool for the application of Design-to-Cost (DtC) rules in HPDC sector.

2. State of the art on cost estimation methods applied to manufacturing processes

HPDC is an important process in the manufacturing of high volumes and low cost components for the automotive, household appliances and electronic industries [1]. Liquid metal, generally aluminium, magnesium or zinc, is injected into the die at high speed (30-100 m/s) and under high pressure through complex gating and runner systems [2]. The HPDC process consists of several steps, from the release agent spraying out the die to the opening and closing of the die [3]. Fig. 1 highlights the overall HPDC process cycle.

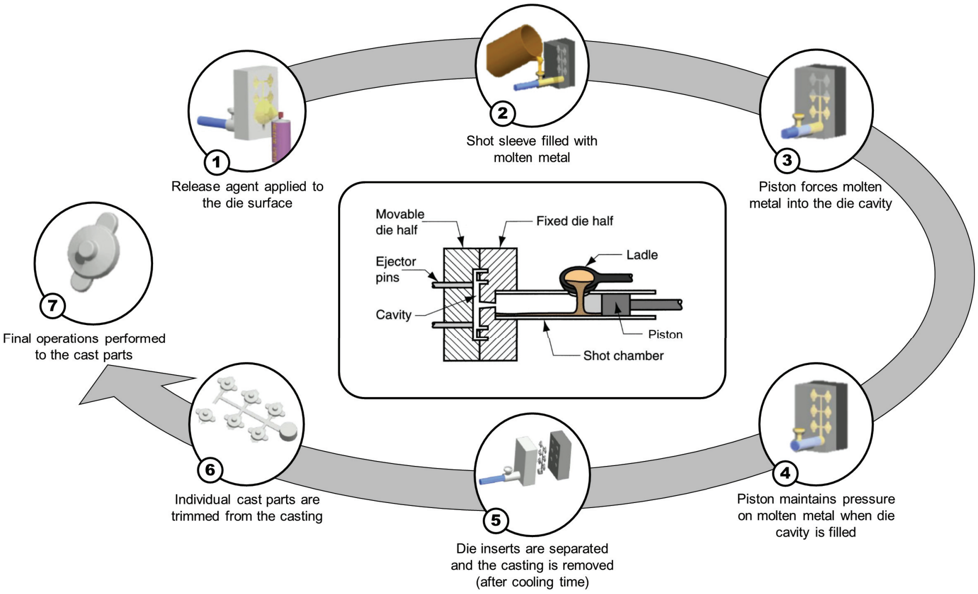

Fig. 1. HPDC process overview.

Cost estimation is a preparatory activity that must be done as a basis for the design activities (e.g. Design to Cost) [4]. The cost estimation is an activity carried out at different stages of the product-process design (e.g. conceptual design, detail design, etc.) [5]. The cost estimation requires a classification of the cost items both for the material and the manufacturing process as well as for the definition of a cost model [6]. It is well known that the cost estimation task is assisted by the specific knowledge of the company, which results from experience and accumulated business results [7]. For an appropriate manufacturing cost estimation, process planning and production planning aspects are required [8]. Process planning includes the generation and the selection of machining processes, the sequence, the machining parameters, etc. [9] [10]. Among the many methods for cost estimation, they can be classified as: (i) *knowledge-based methods* grounded on the estimator experience, (ii) *analogical methods* based on the similarity with existing products, (iii) *analytical methods* based on elementary tasks decomposition and, (iv) *parametric methods* founded on the relations between product characteristics and their cost [11]. The following Table 1 summarizes the characteristics of each method.

Table 1. Characteristics of the cost estimation methods.

	Accuracy (how the method is accurate and consistent with the real final cost)	Robustness (how the method can easily adapt to the product with different features, dimensions, etc.)	Subjectivity (how the method is independent by the end-user)
Knowledge-based methods	Low (depends on product geometry)	Low	High
Analogical methods	Low (depends on product geometry)	Low	Medium
Analytical methods	High	High	Low
Parametric methods	Medium	High	Low

In case of casting processes, rough cost estimation has been approached mainly using parametric (rule-based) models including casting weight and shape complexity [11]. Parametric models have been developed for tooling cost, driven by part complexity, which is computed from the part solid model [12]. In some cases, parametric methods use geometric features recognition (e.g. hole, rib, slot, etc.) of the product and tooling as the basis for cost estimation [13]. Anyway, the literature models for cost estimation can be considered accurate enough for a comparative cost analysis of the various casting processes at the design phase. However, they are not enough detailed to be used for analytically optimizing the product geometry/features based on the specific process characteristics. In addition, each casting process (e.g. gravity, HPDC, etc.) has specific peculiarities and requires a specific cost model. The commercial software tools for the cost estimation of die casted parts (e.g. aPriori and CustomPart.NET), which follow an analytical approach, do not foreseen a detailed cost breakdown based on the elementary operations characterizing the product. They work as "black boxes" that do not help product and production engineers in founding the product features related to the process criticalities.

A systematic approach for cost estimation of HPDC process will give accurate results and better insights (cost breakdown) than the general method currently used in practice. Moreover, the cost estimation model and DtC rules need to be coupled to provide a holistic framework for cost analysis and optimization and to give a tangible tool for the daily design activities.

3. The cost estimation model for HPDC

The analytical cost model presented in this work has been made by combining several contributions coming from the scientific and industrial literature with the knowledge of skilled technicians (cost engineers, production technologists, plant managers and designers). A spreadsheet has been used as a tool for the implementation of the current model. The cost model (Equation 1) considers the raw material (C_{mat}), the transformation process (C_{pro}), the accessory operations ($C_{accessory}$) and the setup operations (C_{setup}). The investment cost is beyond this work. The following sections present the details for each cost item. For a better understanding of the equation items, Annex I contains the list of parameters used by the equations, each one characterized by a symbol, unit of measure and description.

$$C_{tot} = C_{mat} + C_{pro} + C_{accessory} + C_{setup} \tag{1}$$

3.1. Raw material cost

The raw material cost (Equation 2) is the most impacting item in the assessment of the overall cost. Indeed, its share is generally greater than the 50% of the total cost of a component [7]. It considers the raw material purchase cost, the melting operations (C_{rawtra}, energy consumption of the ovens and material lost by sublimation, depending by the melting process) and the revenues from the scraps and discarded parts (C_{rawscr}) due to the recyclability of the alloys used in HPDC (alloys can be recasted more times for obtaining new products). For the raw material calculation, a defect rate (D_{rate}) needs to be considered since not all the molten metal become a compliant part.

$$C_{mat} = (V_{raw} \cdot \rho \cdot CU_{raw} + C_{rawtra} - C_{rawscr}) \cdot \left(1 + \frac{D_{rate}}{100}\right) \tag{2}$$

The raw material volume (V_{raw}) refers to the volume of the part, overflows and filling system. The volume of the overflows and filling system are calculated using empirical formulas defined in [14]. The unitary cost of the raw material (CU_{raw}) is a value defined by national (e.g. ASSOMET for Italy) and international organizations (e.g. London Metal Exchange). A manufacturing firm can get the molten metal from external furnaces or by using internal furnaces. For this latter, Equation 3 defines the transformation cost.

$$C_{rawtran} = C_{ene} + C_{lost} + C_{lab} + C_{ope} + C_{depr} \tag{3}$$

The previous cost items strongly depend by the furnaces used for the melting process. A melting process mainly consists of two furnaces, the first one used for melting the solid alloy (located within the melting department) and the second one for holding the liquid alloy (combined with the press). The first process is realized by using centralized furnaces if the company is specialized on few alloys (< 5 materials), with high production volumes (> 2˙000 tons/year). Stack, reverberatory and crucible furnaces are those ones used for this aim. The cost for the holding phase is considered within the casting process since this kind of furnaces are integrated with the high-pressure die-casting cell.

The energy cost (C_{ene}) required for melting the material is calculated using thermodynamics formulas. The energy cost is a function of the melting temperature of the material, heat capacity, raw material weight and unitary cost of the energy vector of the furnace. The cost of the material lost during the melting and degassing process (C_{lost}) depends by the melting and degassing yields. The first one is a function of the alloy melted each year by a furnace. Typical values are 0.55 – 0.45 for a crucible furnace (valid respectively for a production rate of 200 – 1˙300 tons/year), 0.06 – 0.02 for a reverberatory furnace (valid respectively for a production rate of 300 – 4˙500 tons/year) and 0.024 – 0.022for a stack furnace (valid respectively for a production rate of 3˙500 – 11˙000 tons/year). The degassing yield is a constant value that depends by the degasser used. The melting process does not imply only the energy consumption, but also other direct (labour C_{lab} and operation C_{ope}) and indirect costs (furnace depreciation C_{dep}). The labour cost, for each component, is calculated considering the workers involvement (generally one for each furnace) during the melting process. The operation cost considers other costs such as the overheads and maintenance. The hourly cost is a constant value defined by the enterprise according to the furnace dimension. The furnace depreciation follows the common formulas used in economics, considering the furnace lifespan (commonly 20 years) [15], the working hours each year (8˙760 hours excluding the idle time) and the depreciation index (commonly 5%) [16].

The raw material cost considers the revenues (C_{rawscr}) coming from the scraps (filling systems and overflows) and the defected parts (calculated according to the defect rate D_{rate}). The cost model distinguishes between lubricant-contaminated (overflows) or uncontaminated material (filling system, gate and die-casted part). The unitary cost of the scarps is different for these categories because the contaminated material cannot be used for manufacturing new compliant products. The uncontaminated scraps can be recasted for manufacturing high quality products.

3.2. Processing cost

The processing cost item consists in analytically evaluating the die-casting process following the steps depicted in Fig. 1. The die-casting process is carried out by an automatic cell made by a holding furnace, a die-casting press, a lubrication system, a robot for removing the die-casted part from the press, a water/oil bath for cooling the part and a trimming press (for convenience, the press can be located outside the cell). The processing cost (C_{pro}, Equation 4) is calculated by multiplying the hourly cost of the cell (CU_{hpdc}) by the processing time (T_{cycle}). The defect rate, which mainly depends by the part complexity and die wear, increases the process cost. Moreover, for high production volumes, the die contains more cavities ($N_{cavities}$); hence, the process cost for a single part is obtained splitting the overall cost by the number of cavities.

The die-casting process mainly consists of two phases, the part die-casting, which transforms a liquid material to a solid part and the part trimming for removing the overflows, filling system and splitting the cavities. These phases occur in parallel, so that the overall cycle time is determined by the longest phase (Equation 5). The penalty factor (P_f) corrects the standard cycle time for considering the part roughness, dimensional and geometric tolerances.

$$C_{pro} = \frac{\frac{CU_{hpdc}}{3600} \cdot T_{cycle} \cdot (1 + D_{rate})}{N_{cavities}} \tag{4}$$

$$T_{cycle} = MAX \begin{Bmatrix} T_{pouring} + \left(T_{filling} + T_{cooling} + T_{lubrication}\right) \cdot \frac{P_f}{100} + T_{eopening/closing} + T_{extraction} \\ T_{liquidcooling} + T_{trimming} + T_{rotation} \end{Bmatrix} \tag{5}$$

The equations for calculating the pouring, filling, cooling, lubrication, opening/closing and extracting times, which derive from [17], have been adapted and modified for the HPDC process.

The pouring time is a function of the raw material volume through an empirical value that represents the pouring rate (this is a constant value defined for avoiding a turbulent flow of the liquid alloy). The filling time mainly depends by the minimum thickness of the part. Indeed, it is necessary to fill the die before the solidification process begins (it happens close to the thinnest volume of the part). The other most-influencing factor is the material of the part, which determines the characteristics temperatures for the die-casting process (melting, liquidus and die temperatures). The cooling time is a function of the maximum thickness of the part because the part can be extracted from the die only when the temperature of the thickest areas is under a specific threshold value. As for the filling time, also the material properties influence the timespan of this operation. The lubrication time is a function of the frontal area of the part, calculated by projecting the part along the extraction direction. The time required by the press for opening and closing the die is a characteristic of the machine (dry-cycle time). Moreover, that time depends by the die complexity. For instance, in case of sliders, required for realizing parts with undercuts, the dry-cycle time is increased for allowing the movements of the sliders and avoiding the occurrence of defects on the parts. The time for extracting the part from the die depends by the overall dimensions of the part (it is a proportional function of the part weight). The time for cooling the part within a bath of water/oil mainly depends by the maximum thickness of the part and by its material. The equation is similar to that one used for calculating the part cooling time within the die. The time for the filling, cooling and lubrifcation operations of the die-casting phase generally depends by the product features and attributes, such as the roughness and presence of dimensional and geometric tolerances. The penalty factor (P_f) for roughness ($P_{roughness}$), dimensional tolerance (P_{dimtol}) and geometric tolerances (P_{geotol}) has been defined for this aim (Equation 6).

$$P_f = \left(P_{roughness} + P_{dimtol}\right) \cdot P_{geotol} \tag{6}$$

Errore. L'origine riferimento non è stata trovata. summarizes the $P_{roughness}$ value as a combination of the part roughness and the dimensional tolerances.

Table 2. Penalty factor for the part roughness.

Roughness	Tolerances are not difficult to obtain	Tolerances are difficult to obtain
3.2 – 12.5 µm	1.16	1.2
12.5 – 30 µm	1.17	1.16
30 – 50 µm	1	1.02

The complexity factor (“tolerances are difficult to obtain”) is a Boolean parameter. It is *TRUE* if “*The part has external undercuts*” AND “*The part thickness percentage change is greater than 50%*” AND “*The part requires tight tolerances on the separation line*”. According to the Table 2, a smoother surface implies a higher process time, since the injection pressure has to be maintained for a longer time. The table has been defined formalizing the knowledge of several companies involved during the development of this research study. Tight dimensional tolerances (Table 3) implies a longer cooling phase for reducing as much as possible any possible deformation of the part outside the die.

Table 3: Penalty factor for the part dimensional tolerances

Dimensional tolerances	$P_{dmintol}$
0.05mm < tolerance ≤ 0.075mm	0.21
0.075mm < tolerance ≤ 0.125mm	0.13
0.125mm < tolerance ≤ 0.25mm	0.09
0.25mm < tolerance ≤ 0.35mm	0.03
> 0,35mm	0

The penalty factor for the geometric tolerances depends by the shape of the part. The most important aspects considered for its characterization are: (i) slenderness, (ii) ribs (i.e. multidirectional, unidirectional, concentric, radial, peripheral/no peripheral), (iii) thickness variation and (iv) other details (i.e. shape similar to a frame, presence of lateral projections). Table 4 contains an extract of a detailed table defined in this study.

Table 4: Penalty factor for the part geometry (extract of a more detailed table)

Feature1	Feature2	Feature3	P_{geotol}
Slender part with an almost constant thickness (<20%) $IF\ \frac{L}{W} < 10\ THEN$ Slender part	Peripheral ribs	Multidirectional or concentric ribs	1.01
		Radial or unidirectional ribs	1.04
	No peripheral ribs	Multidirectional or concentric ribs	1.06
		Radial or unidirectional ribs	1.09
…	…	…	…

3.3. Press selection

Most of the parameters used for calculating the cost depend by the press. According to the commercial catalogues of the press manufacturers, the clamping force, the stroke and the maximum die dimensions are the parameters used for the machine selection. The required clamping force (C_{force}) depends by the pressure applied during the filling phase, which considers also an intensification factor depending by the kind of part (standard, technical or special), the frontal area of the cavities and filling system and the number of cavities. The frontal area of the filling systems, for a single cavity, is indirectly calculated considering the timespan for the filling phase, the volume of the overflows and part and the suggested flow speed at the gate.

The required press stroke (*Stroke*) mainly depends by the part dimension along the extraction direction, plus a tolerance for safety reasons. The die dimensions (H_{die}: height and L_{die}: width) depend by the number of cavities, overall dimension of the part (perpendicular to the extraction direction) and offset required between the cavities. The machine is valid if all the following conditions are respected at the same time: (a) Machine clamping force > C_{force}; (b) Machine stroke > *Stroke*; (c) Machine horizontal die dimension > H_{die}; (d) Machine vertical die dimension > L_{die}.

3.4. Cost for accessory and setup operations

The cost of a die-casted part needs to consider additional cost items related to the initial setup of the process (C_{setup}), maintenance operations and consumables required by the process ($C_{accessory}$) (Equation 7). The setup refers to those operations required to start a production, so that the related cost should be split by the batch size (B_s). For instance, before starting a production, it is necessary to unload the dies (for die-casting and trimming) used for the previous production and load those ones for the current production. The related time mainly depends by the overall dimension of the die. The time for the initial setup (i.e. clean the press, setup the die-casting parameters, connect the cooling system) is generally a value that depends by the press. It increases with the press size (clamping force). The setup phase generates several scraps and defected products, which are discarded/recasted. The number of such components mainly depends by the part complexity, defined by the parameters $P_{roughness}$, $P_{dmintol}$ and P_{geotol}.

$$C_{setup} = \frac{(T_{mhpdc}+T_{mtrimming}+T_{initsetup})\cdot\frac{CU_{hpdc}}{3600}+C_{scraps}}{B_s} \tag{7}$$

The accessory cost ($C_{accessory}$) is the sum of the maintenace and consumables costs. The maintenance cost mainly refers to the cost for maintaining the press cylinder, piston and the die-casting and trimming dies. The cylinder and piston cost of the press depend by the size of the press itself, according to the maintenance plan. The die-related costs depend by its complexity (the die complexity is directly proportional to the part complexity) and by the machine. The cost of the consumables mainly refers to the consumption of lubricant, used for cooling the part (function of the cavity area) and lubricating the press (function of the press size).

4. Test of the analytical model in real manufacturing contexts: case studies analysis

Several case studies have been used within this work to test the efficiency of the model. In particular, two gas flame-spreaders and one radiator have been reported as examples of this process (Fig. 2).

	Burner		Burner 3 rings		Heater element	
	Calculated value	Reference value	Calculated value	Reference value	Calculated value	Reference value
Total cost - Ctot [€]	0,31	0,33	1,02	1,07	4,39	4,58
Raw material Cost – Cmat [€]	0,20	0,23	0,61	0,63	3,71	3,81
Processing Cost – Cpro [€]	0,06	0,06	0,24	0,26	0,55	0,61
Accessory operations Cost – Caccessory [€]	0,01	0,01	0,02	0,04	0,02	0,04
Set-up operations cost – Cset-up [€]	0,04	0,03	0,15	0,14	0,11	0,12
HPDC process efficiency	48%	44%	55%	52%	50%	49%
Total casting weight [kg]	1,64	1,82	0,99	1,02	11,01	11,66
Cast product weight [kg]	0,80	0,79	0,55	0,54	5,4	5,5

Fig. 2. Cost estimation results for the proposed case studies.

The case studies, characterized by different dimensions, features, attributes and properties, represent a broad range of aspects and issues of the HPDC manufacturing process. Moreover, these products are currently under production in some of the HPDC manufacturing companies involved in this study and a reference value about the actual cost of the product can be obtained for a comparison.

Results highlight that the maximum error in estimating the total cost (C_{tot}) for the three case studies is 6%. In particular, this value refers to the first burner example in which the total cost is very low and a noticeable difference is shown for the raw material cost (C_{mat}). This difference is caused by the total casting weight and more specifically considering the dimensions of the gating systems, which seems over-dimensioned in the reference actual model. For the other two examples (burner 3 rings and heater element), the maximum error in the total cost is approx. 4%. It is worth to notice that the energy cost item (C_{ene}) included in the raw material cost has been retrieved as approximation of the current batch already performed by the companies for the proposed products. It means that possible errors on the raw material cost can be introduced by this item. The highest error in the cost estimation refers to the accessory and set-up operations (approx. 50% cost deviation for the Burner 3 rings and for the Heater element). However, their contribution to the total cost is low (less than 10%).

5. Conclusion

The present paper defines an analytical model for the cost estimation of products realized with the HPDC process. The analytical model takes into account different cost items and links the product features (e.g. geometrical, dimensional, etc.) with the process parameters (e.g. batch, cooling time, etc.). The relationships between geometrical features and cost items give an accurate result in terms of cost breakdown as demonstrated by the three case studies. The maximum error calculated by using the proposed model is approx. 6% for the total cost. It is mainly caused by the raw material cost item, which takes into account the gating system weight and the energy cost necessary for the melting process. The lower accuracy is noticed for the accessory and set-up cost items even if their impact on the total cost is almost negligible for high production volumes. This result is in line with the results observed in literature considering analytical models applied to consolidated manufacturing technologies (e.g. turning, milling, drilling, molding, cutting and bending, etc.) [18][19]. Therefore, the adoption analytical models, such as that one presented in this paper, allows manufacturing companies making decisions about the technology to adopt or to exploit for a given component geometry/feature.

Future work will aim at improving the model accuracy for the critical cost items, avoiding as much as possible the subjectivity in the cost estimation process. Moreover, an important step forward will be the validation of the proposed model taking into account other cost models from the scientific literature and commercial software tools. In addition, the proposed cost estimation model can be coupled with the development of a DtC method to support designers in choosing the best product's geometries and features early in the design phase.

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6. Appendix 1

Symbol	Unit	Description
C_{mat}	[€]	Cost of the raw material and relative melting process
C_{pro}	[€]	Cost of the casting process (injection, cooling, extraction and trimming)
C_{setup}	[€]	Cost of the setup operations before starting the production
$C_{acccessory}$	[€]	Accessory cost (consumable and defected products)
V_{raw}	[mm^3]	Volume of the raw material
CU_{raw}	[€/Kg]	Unitary cost of the raw material ready for the melting process
ρ	[Kg/m^3]	Material density
C_{rawtra}	[€]	Cost for melting the raw material
C_{rawscr}	[€]	Cost (revenue) of the scraps reintroduced within the furnace
D_{rate}	[%]	Defect rate for the casting process
C_{ene}	[€]	Cost of the energy (e.g. Gas, electricity, etc.)
C_{lost}	[€]	Cost of the raw material lost by sublimation
C_{depr}	[€]	Cost related to the furnace depreciation
C_{labo}	[€]	Cost of the labor
C_{ope}	[€]	Cost for machines and tools supporting the melting process
CU_{hpdc}	[€/hour]	Unitary cost of the high pressure die casting press
T_{cycle}	[second]	Time for a complete die casting cycle
$N_{cavities}$	[-]	Number of cavities of the mold
$T_{pouring}$	[second]	Time for pouring the liquid alloy within the die
$T_{filling}$	[second]	Time for filling the die under the thrust of the piston
$T_{cooling}$	[second]	Time for cooling the alloy within the die
$T_{lubrication}$	[second]	Time for lubricating the die
P_f	[%]	Penalty factor for considering the part complexity
$T_{opening/closing}$	[second]	Machine dry cycle time
$T_{extraction}$	[second]	Time for extracting the part from the die
$T_{liquidcooling}$	[second]	Time for cooling the part before the trimming
$T_{trimmin}$	[second]	Time for the trimming operation
$T_{rotation}$	[second]	Time required by the robot to move the part among the press, cooling bath and trimming press
$P_{roughness}$	[%]	Penalty factor that considers the surface roughness
P_{dimtol}	[%]	Penalty factor that considers the dimensional tolerances
P_{geotol}	[%]	Penalty factor that considers the geometric tolerances
T_{mhpdc}	[min]	Time for mounting the high pressure die casting die
$T_{mtrimming}$	[min]	Time for mounting the trimming die
$T_{initsetup}$	[min]	Time for setting-up the machines
C_{scraps}	[€]	Cost of the discarded components
B_s	[-]	Batch size