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Hybrid forecasting modelling of cost and time entities for planning and optimizing projects in the die-cast aluminium industry

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A B S T R A C T

The techniques employed to manage an industrial project are based on tools that aim to achieve the objectives set by an organization. Most of these techniques consider the development of operative and predictive models. The difficulty in developing project planning models relies on estimating large sets of parameters and the need to include model sections of poorly identifiable, that increase costs and time. This work develops a hybrid forecasting model for all the phases that make up die-casting projects through a series of parameters and sub-models that contemplate the particularities of each case, thereby achieving greater precision in the forecast. The model identifies the cost and time factors that affect project planning, specifically in the die-casting industry, and intends to predict their future behaviour when certain initially given conditions are modified. To estimate the parameters of the hybrid model, several factors in the processes were considered that interact in this industry, such as primary matter costs and activities associated to the process. The considered processes that have a substantial economic impact on the implementation of the project were selected. The criteria for this selection considered identifying the relevant parts of the design and manufacturing in the die-casting industry. Process factors such as the Cost of aluminium and its related activities, whose processes will be grouped into cost and time entities to build a set of metrics that allow better control over them. Finally, the proposed model is based on analytical, parametric, and analog methods that achieve accuracy greater than 85 % in predicting the time and Cost of the process.

A R T I C L E   I N F O

Keywords:
Hybrid models;
Entity modelling;
Project planning;
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Aluminium die-casting;
Cost factors;
Time factors;
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1. Introduction

Project planning is useful for improving time and costs in company projects involving management techniques. These approaches have been designed and developed since the middle of the 20th century [1-4] intending to improve the outcome of project planning, the development of qualitative [5-7] and quantitative models [8-11] has ben considered. These models have motivated the implementation several optimization strategies that have contributed to reducing operation costs and operative times of processes included in the project.

Developing valuable models (usually known as estimation models) in project planning requires analyzing historical information regarding the effects and results of different operative strategies and control techniques implemented in previous projects. Due to the specific conditions of each productive sector where the estimation models could be applied, they must depend on different operative, commercial, and economic variables, including the technology for developing the project, raw materials, workforce, etc. These highly specialized models have been developed for sectors as varied as software [12], construction [13-14], aerospace [15, 16], and automotive [17, 18], machining [19], among others. Specifically, the use of models for estimating manufacturing costs and time, widely used to determine the Cost of forged parts [20], rotating parts [21], manufacturing of die-casting molds [22], and preformed parts employing die cuts [23].

The importance of estimation models in manufacturing processes lies in their ability to accurately predict the costs of primary materials and methods and operative times. In addition, the successful models considered specific needs and practical implications that are part of the environment in which the project is developed. Also, on many occasions, the precision and speed in estimating costs and operative times are associated with the final purchase order, which the customer defines.

With the intention to determine goods production times and costs, the manufacturing processes can be calculated using several methods, like the analytical methods that break down manufacturing activities into their elementary parts. However, despite the benefits of these models, their descriptions usually have many parameters. They are very nonlinear and may not consider some problematic aspects of the model.

A different technique for developing the estimation model is based on non-parametric methods that could produce a mathematical representation of productive relationships using the information generated by the industrial sector under study. These non-parametric models can be complemented with analogous methods to classify product indices according to their dimensional and quality characteristics [24]. All these methods have been successfully used in estimating time and costs for diverse projects of various industrial sectors, including metal mechanics.

In the aluminum die-casting industry, the existing estimation models focused on several factors that affect the manufacturing process. An example of such a method is the model developed by Madan that focuses on determining the optimal Cost and time of production, depending on the geometric conditions of the part; through these data, they determine the number of cavities necessary for the die casting dies [25]. On the other hand, the model developed by Sung focuses on simulating the pores within the die-cast process. Specifically, this model considers factors such as trapped air during the die-casting process caused by the design of the die-casting mold and the properties changes by anisotropic composition due to the die-cast process conditions [26].

Srivastava proposes a model to determine the conditions that cause thermal fatigue, and cracking of casting die [27]. The work presented by Tsoukalas produces a model to determine the porosity of $AlSi_9Cu_3$ aluminum used in die casting. The model is supported by genetic algorithms that validate as main variables the die casting temperature, the die casting mold temperature, and the speed of the phases of die casting [28].

The models described above establish connections between operative conditions in the die-casting process. Nonetheless, they are not formally related to the economic aspects of the final product and its delivery time to the final consumer. Nowadays, many companies apply parametric or probabilistic cost estimation methods. The characteristics and rapid implementation are unique elements of these models. However, these models use synthetic data obtained by approximating the total production cost and overall production time and assuming some desired features for the final product.

The product features can be diverse depending on the design requirements and manufacturing activities. The main problem of this production process is the lack of information about the cost structure and the product's manufacturing processes.

As a result, it became difficult for the designer to visualize the necessary modifications that should be applied to the model to reduce costs in the quotation activities. Such a fact makes it complex to assign only a cost value to the product, limiting the transparent negotiation of the Cost and consequently causing a delay with the customer.

The indirect costs are other factors to consider in the product cost structure, materialized by the support activities. Besides, the causal relationship between cost objects (products and services) and consumable resources is difficult to assess. This evaluation can be solved using traceability, which makes cost analysis explicit in a network with its incorporation into products or services, which is difficult to achieve with the traditional cost estimation approach.

The application of a hybrid model allows accurate forecasting of the phases that make up the processes of die-casting projects. Hybrid models have significant advantages in their use, as shown in the following key applications: a) the optimization of manufacturing processes for obtaining fiberglass in the automotive industry [29], b) the improvement of pill production processes in the pharmaceutical sector [30], and c) in the construction of metal structures at high temperatures through process planning [31]. Likewise, other critical applications for the application of hybrid models that have advantages in precise parameterization in industrial activities are, for example, for inventory control [32], electrical energy consumption [33], in the handling of the materials [34] and the costing for the manufacture of turbines [35].

The advantages of using hybrid models for process planning lie in the flexibility of these models and their ability to adapt to a significant number of features that they may have, selecting the model that best suits the characteristics to be predicted [36]. However, it is also essential to consider that the main disadvantage of its use lies in the large number of data that must be used to achieve considerable precision of the model.

This study presents a data-driven hybrid model to asses costs and process time in the die-cast aluminum industry. The model shown in this work uses analytical, parametric, and analogous methods. Among the variables that are considered for the model development are: a) the Cost of the raw material (which is a determining factor in signing long-term contracts with the automotive and aerospace sector), b) the processing time, and c) the Cost of the operations that will be carried out for the manufacture of the piece, including intermediate process such as die-casting, grinding, die-cutting, drilling, shot blasting, and packing, among others. The goal of the modeling process is to generate a projection that allows controlling the project plan of the die-casting process. In addition, the proposed model considers technical and economic aspects essential for developing projects in the die-casting industry. The successful development becomes the model into an auxiliary tool for estimating the costs and delivery times of the customer product. As a result, the problem of estimating the Cost and time in die-casting projects focuses on constructing a model that can be described as an integral formulation. Such completeness is a consequence of considering a series of sub-models that allow its adaptation to the specific characteristics of the casting process to predict. Hence, this work considers three fundamental aspects of the model design:

- The changes in the price of aluminum in international markets.
- The changes in the production process that have more significant impact on the Cost and the time of the project (die casting, grinding, drilling, and packing, among others).
- The model aspects related to the manufacture of the die-casting mould.

This work is organized as follows. Section 2 is the mathematical basis and the details of the construction of the model. The description of the data set used for its test is included in this part. Section 3, the simulation results achieved by the model. Finally, Sections 4 and 5 close the study with the model's accuracy and relevant conclusions describing some problems related to the discussed topic.

2. Model construction

For the development of the model proposed in this work, it was necessary to estimate the following steps:

- Determination of cost and time entities (CTE) divided according to each primary activity.
- Development of CTE for the manufacturing of parts and manufacturing tooling.
- The CTE for the raw material only considers the Cost, not the time, since it is a complementary value chain activity.
- The CTE's information is gathered from various productive projects to carry out the simulations and the relationships between the projects' time, Cost, and weight.

- The weight directly determines the production costs and expenses to complement the Cost Entity.
- The equations for each CTE are formulated according to the information and the simulation.

2.1 Cost and time entity

For die-casting, estimating Cost and time is the crucial combination for predicting how much it will cost and how long it will take to make a certain product or many products through the analysis of the particularities attributed to it [37]. To identify and control these intrinsic particularities of each development, CTE is proposed. Developed for the analysis of the Cost and time of each critical activity, it provides information related to the added value of the project, so the CTE will allow the estimation of the Cost and time between the products, considering the Cost per kilogram and the time of the product manufactured for homogeneity.

The CTE (Fig. 1) is composed of two elements. Its first element is the Cost Entity (CE), whose primary function is controlling each project phase's Cost. The Time Entity (TE) is its second element, which determines the time assigned to each activity to be carried out.

It's essential to define once the homogeneous resources for the project are stable and interdependent. They are stable because of the imputation of these within the productive chain, which is given by $\frac{\beta}{X}\left(\text{i.e.}, \backslash\frac{\beta}{min},\frac{\beta}{kg}\right)$. Notice that each resource does not need to change depending on the product. These components are interdependent since the resources are consumed in the same proportion by one element in any way the product is used.

Assuming that $R_i = [k\colon k \in K]$ represents the number of resources consumed by the CTE_i, TE_i or CE_i to realize the i_{th} activity gave by A_i. If $\left[y_i^k(X_i) = X_i\alpha_k\right]$ is equivalent to the number of resources k consumed by carrying out the activity A_i under the condition X_i (where α_k is the coefficient with which resources k are consumed) and if $C_k = y_i^k(X_i)$ and $T_k = y_i^k(X_i)$ is the allocation fee corresponding to the Cost and time of the resource units and units k. Therefore, Eqs. 1 and 2 are basic for the determination of Cost and time:

$$CE = \sum_{k \in R_i} C_k\left(y_i^k(X_i)\right) \tag{1}$$

$$TE = \sum_{k \in R_i} T_k\left(y_i^k(X_i)\right) \tag{2}$$

The definitions for the distribution of the Cost of a resource would be the following:

- Machining $(nb)\alpha_k\left(\frac{h}{nb}\right)$ an imputation fee $\left(\frac{\beta}{h}\right)$.
- $\left((X_i)\alpha_k\right)$ is an imputation fee, determined by Cost based on weight.
- $y_i^k(X_i)$ is an imputation fee, determined by the time.

The α_k is the coefficient with which resource k is consumed, nb is the identification of the Cost for machining. The coefficients to determine the degree to which resources are consumed within the project activities were determined through statistical relationships obtained from 20 projects within the die-casting industry.

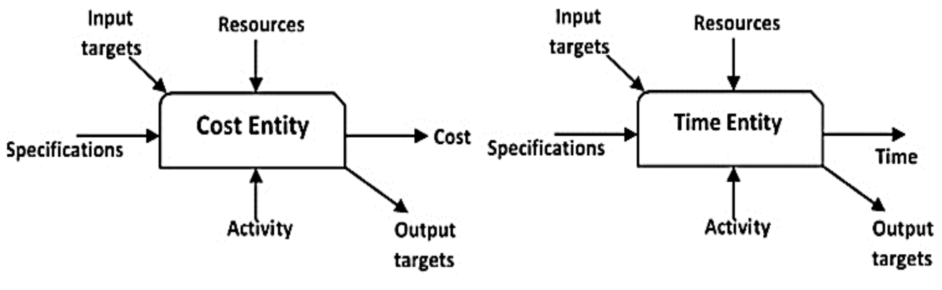


Fig. 1 Graphic representation of the CTE

Cost and time entity pattern

The Cost and Time Entity Pattern (CTEP) is a macro-entity that meets the characteristic of homogeneity of the resources of the CTE. CTEP simplifies the model for determining Cost and time and helps establish an overview of the manufacturing chain.

The basic information for estimating costs and time in projects of the die-casting industry is represented in the Scheme of the Cost and Time Entity Patterns (SCTEP) shown in *supplementary file 1*. The SCTEP is built based on the product's characteristics, such as; physical specifications of the product (weight and type of aluminum), manufacturing (the type of surface finish, drilling, packing, among others), and the tooling (number of cavities, volume, etc.). For the estimation of the Cost and time in the design as well as in the manufacturing, the purchase order is used. Such application allows us to quantify the *flexibility* of the order and give an adequate estimation of the phases necessary to develop the project, so the purchase order represents a priority aspect [38].

It is important to establish that the CE and TE maintain the homogeneity condition understood as the similarity of the activities between the parameters; resources, activities, inputs, and outputs. Therefore, the union of the parameters and the sum of the costs and elementary times of the different cost entity patterns (CEP) and time entity patterns (TEP) are described in Eqs. 3 and 4

$$CEP = \sum_{i \in N} \sum_{k \in R_i} C_k \left(y_i^k (X_i) \right) \tag{3}$$

$$TEP = \sum_{i \in N} \sum_{k \in R_i} T_k \left(y_i^k (X_i) \right) \tag{4}$$

where N is the number of CE that is part of CTEP.

General model for determining cost and time

Once the elements that will be part of the model structure have been defined, it is important to identify the main activities to be modeled. For this work, the activities taken into consideration are:

- The price of the metal.
- The manufacturing time of the product.
- The Cost of the Product.
- The manufacturing time of the die-cast tooling.
- The Cost of the die-cast tooling.

Considering it, the models proposed for the determination of the total Cost and time of the project can be represented as Eqs. 5 and 6.

$$Cost_{Total} = Cost_{RM} + Cost_{manufacturing} + Cost_{Tooling} \tag{5}$$

$$Time_{Total} = Time_{manufacturing} + Time_{Tooling} \tag{6}$$

In some cases, there may be the possibility that the customer no longer requests a part of the project; for example, the customer can provide the tooling. In consequence, it would only be necessary to establish the Cost of the raw material and manufacturing. A binary matrix can be constructed to establish this relation, where *zero* identifies an activity that does not occur and one that occurs in the project.

3. Methodology and primary results

CTEP$_1$ of the raw materials

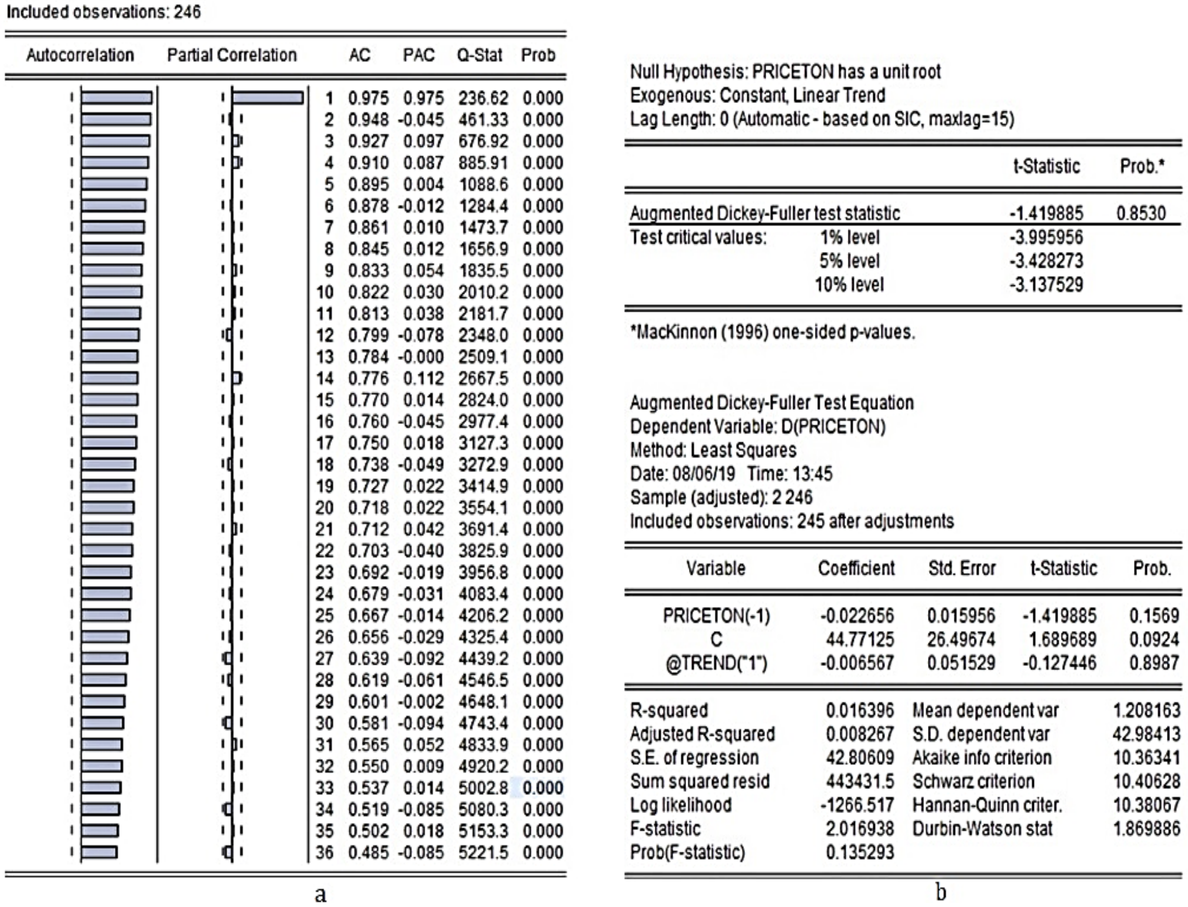
In this case, the CTEP$_1$ for the raw material will include only the calculation of the Cost of aluminum, for which the historical data reported by the London Metal Exchange (LME) of the Cost in dollars per ton will be used. The start date of data collection was January 1, 2016, and the end of it on May 25, 2019. The database contains five monthly readings that will give 246 data for the analysis, this information can be consulted at *supplementary file 2*.

Intending to determine the most accurate forecast model, it is necessary to apply tests to establish the stationarity of the time series, for which the Eq. 7 gives the correlation function of the sample [39].

$$r_k=\left(\sum_{t=1}^{T}(x_t-\bar{x})(x_{t-k}-\bar{x})\right)\left(\sum\nolimits_{t=1}^{T}(x_t-\bar{x})^2\right)^{-1} \tag{7}$$

Therefore, it is possible to develop the correlogram shown in Fig. 2(a), in which the analyzed series of the LME presents a simple and partial first-order correlation, which determines that the immediately previous data are the ones that have the greatest influence on the value of the following data.

$$d=\left(\sum_{t=2}^{T}(e_t-e_{t-1})^2\right)\left(\sum_{t=2}^{T}e_t^2\right)^{-1} \tag{8}$$



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Included observations: 246

 Autocorrelation   Partial Correlation      AC     PAC   Q-Stat  Prob

                                        1  0.975  0.975  236.62  0.000
                                        2  0.948 -0.045  461.33  0.000
                                        3  0.927  0.097  676.92  0.000
                                        4  0.910  0.087  885.91  0.000
                                        5  0.895  0.004  1088.6  0.000
                                        6  0.878 -0.012  1284.4  0.000
                                        7  0.861  0.010  1473.7  0.000
                                        8  0.845  0.012  1656.9  0.000
                                        9  0.833  0.054  1835.5  0.000
                                       10  0.822  0.030  2010.2  0.000
                                       11  0.813  0.038  2181.7  0.000
                                       12  0.799 -0.078  2348.0  0.000
                                       13  0.784 -0.000  2509.1  0.000
                                       14  0.776  0.112  2667.5  0.000
                                       15  0.770  0.014  2824.0  0.000
                                       16  0.760 -0.045  2977.4  0.000
                                       17  0.750  0.018  3127.3  0.000
                                       18  0.738 -0.049  3272.9  0.000
                                       19  0.727  0.022  3414.9  0.000
                                       20  0.718  0.022  3554.1  0.000
                                       21  0.712  0.042  3691.4  0.000
                                       22  0.703 -0.040  3825.9  0.000
                                       23  0.692 -0.019  3956.8  0.000
                                       24  0.679 -0.031  4083.4  0.000
                                       25  0.667 -0.014  4206.2  0.000
                                       26  0.656 -0.029  4325.4  0.000
                                       27  0.639 -0.092  4439.2  0.000
                                       28  0.619 -0.061  4546.5  0.000
                                       29  0.601 -0.002  4648.1  0.000
                                       30  0.581 -0.094  4743.4  0.000
                                       31  0.565  0.052  4833.9  0.000
                                       32  0.550  0.009  4920.2  0.000
                                       33  0.537  0.014  5002.8  0.000
                                       34  0.519 -0.085  5080.3  0.000
                                       35  0.502  0.018  5153.3  0.000
                                       36  0.485 -0.085  5221.5  0.000
```

a

```
Null Hypothesis: PRICETON has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 0 (Automatic - based on SIC, maxlag=15)

                                            t-Statistic    Prob.*

Augmented Dickey-Fuller test statistic       -1.419885    0.8530
Test critical values:        1% level        -3.995956
                             5% level        -3.428273
                             10% level       -3.137529

*MacKinnon (1996) one-sided p-values.


Augmented Dickey-Fuller Test Equation
Dependent Variable: D(PRICETON)
Method: Least Squares
Date: 08/06/19   Time: 13:45
Sample (adjusted): 2 246
Included observations: 245 after adjustments

      Variable        Coefficient   Std. Error   t-Statistic    Prob.

    PRICETON(-1)       -0.022656     0.015956    -1.419885     0.1569
         C              44.77125     26.49674     1.689689     0.0924
    @TREND("1")        -0.006567     0.051529    -0.127446     0.8987

R-squared               0.016396   Mean dependent var      1.208163
Adjusted R-squared      0.008267   S.D. dependent var      42.98413
S.E. of regression      42.80609   Akaike info criterion   10.36341
Sum squared resid       443431.5   Schwarz criterion       10.40628
Log likelihood         -1266.517   Hannan-Quinn criter.    10.38067
F-statistic             2.016938   Durbin-Watson stat      1.869886
Prob(F-statistic)       0.135293
```

b

Fig. 2 (a) Aluminium price correlogram for LME, and (b) Dickey-Fuller test

Once the correlogram is obtained, the autocorrelation of the data is determined by the statistical Eq. 8 of Durbin-Watson [39], obtaining a value of 1.869886, establishing no autocorrelation.

$$\Delta y_t=\phi_1+\phi_2^t+\alpha y_{t-1}+\sum_{i=1}^{p}\delta_i\Delta_{t-1}+\varepsilon_i \tag{9}$$

On the other hand, the analysis of the stationarity series is carried out using the Dickey-Fuller test as shown in Eq. 9 [39]. The results are shown in Fig. 2(b), setting a decision value of -3.428349 and -1.420186. As a result, it is established that the time series of the LME is not stationary and have a unitary root, so it is possible to model this PEC through an ARIMA model.

With the main characteristics of the time series determined, such as their autocorrelation and non-stationarity, it is possible to select a model that best adapts to the forecast.

In the mentioned above case, an ARMA model (2,2) was chosen, which will be the model for determining the PEC_1; this determines the Cost of the raw material expressed with Eq. 10

$$PEC_1 = Y_{t-1} + \theta(Y_{t-2} - Y_{t-3}) + \varphi(\hat{a}_{t-1}) \tag{10}$$

where the coefficient values for the self-aggressive part expressed by θ is 0.797492 and for the mobile part expressed by φ is 0.833451, and $\alpha_{t-1} = y_{t-1} - \hat{y}_{t-1}$. This model adjust precisely to the series of the Cost of aluminum.

CTEP$_2$ of Product Manufacturing

To build the CTEP$_2$ corresponding to the manufacture of the piece, the first step is to propose the matrix of activities of the processes used in its manufacture so it is possible to establish the parametric relationships. For this, 25 projects were selected from the *Maquinados e Inyecciones Tecamac SA de CV* client portfolio. This company die-casts more than 45 tons of aluminium annually for clients such as Siemens-Mexico and Donaldson, among others, being a second-order supplier of assemblers such as Nissan and GMC. Therefore, the projects (*supplementary file 3*) cover 87 % of the company's annual production. It is important to mention that this Table will become a binary matrix indicating whether the activity is carried out (1) or not (0).

Once the project has defined the activities, the times required by activity for its manufacture are established, and the relationship between these times and the weight of the piece is established. To achieve this, it is necessary to calculate the number of cycles to be observed given by Eq. 11

$$n = \left(\frac{st}{k\hat{X}}\right)^2 \tag{11}$$

where n is the number of cycles to be observed given that s is the standard deviation of the test, k the desired degree of accuracy that is 95 % and $\hat{X}$ the average time, with this a pilot run is established stating that it is necessary to observe 50 cycles. Hence, the study of times of the 25 projects is carried out according to the activities listed in *supplementary file 3*. The study performed for the Optimized Shield in *supplementary file 4* (named as *part name no. 2* in *supplementary file 3*) is taken as an example.

When time and movement studies were carried out for each case, the data fit the best distribution that resembles its behavior. This allows for generating a more significant number of observations artificially. This setting can be seen in *supplementary file 5*, in the case of Optimized Shield time's *part name no. 2*.

This process is repeated for each of the projects, as well as for the operations that are necessary for its manufacture. With this, it is possible to determine the appropriate distribution type, resulting in more than 7,000 data supporting the forecasts; this process is illustrated in *supplementary file 6* for the die-cast operation.

Construction of the TEP$_{2,1}$ for the time of part manufacturing activities

The data shown in *supplementary file 6* allows us to determine the relevant equations for each process and estimate the time for the manufacture of the piece. The resulting equations are shown in *supplementary file 7*, where Y_i^k is a binary variable that takes the value of 1 if the activity is carried out and 0 if the activity is not carried out. Also, X_i is the weight of the piece to be manufactured.

With the specific equations and metrics that govern each of the TE of $TEP_{2,1}$, the general equation is constructed, which is expressed as follows.

$$\begin{aligned} TEP_{2,1} = \sum\nolimits_{k \epsilon R_i} y_i^k ET_i X_i = {} & Y_i^k(27.36 + 51.87X_i) + Y_i^k\left(0.9068 + 60.65X_i - 89.98X_i^2\right) + \\ & Y_i^k(7.94 + 33.47X_i) + Y_i^k(0.78 + 26.20X_i) + Y_i^k(0.61 + 64X_i) \\ & Y_i^k\left(5.15 + 80.63X_i - 163.27X_i^2\right) + Y_i^k(2.22 + 26.33X_i) \end{aligned} \tag{12}$$

Construction of the $CEP_{2,2}$ for the Cost of part manufacturing

For the construction of the CEP, a characterization of the Cost is made concerning kilograms manufactured; for this, the following descriptions were generated:

- *Workforce vs. weight.* For this relationship, the direct, indirect, and administrative workforce is considered as a whole, considering that a relationship is kept according to the kilograms produced by the company.
- *Gas vs. weight.* Gas is the fuel oil used to fuse aluminum in melting furnaces, the second most important raw material. It is directly related to the number of kilograms produced by the company.
- *Electric power vs. weight.* Electric power allows the operation of the die-casting equipment, as well as the various finishing and melting equipment; the consumption of electrical energy is determined directly by the number of kilograms produced by the organization.
- *Expenses vs. weight.* The expenses are all those agents necessary for the organization to carry out its productive activity but are not delivered in the final product; these are distributed equally in the kilograms produced by the company.

The company history is reviewed for the workforce vs. weight evaluation to establish its correspondence; the data is shown in *supplementary file 8*.

Once the workforce's Cost per kilogram is obtained, the next step to determine the CE is to make the corresponding adjustment in the behavior of the data shown in *supplementary file 11*. In this way, the trend will be analyzed, so we can apply a more suitable model for simulation. This procedure is carried out in the same way for the rest of the costs, leaving the equations as shown in Table 1.

Table 1 Cost of the workforce against sales from December 17 to February 19, in Mexican pesos

CE	Equation	Type of distribution
Workforce	$CE_{2,2,1} = N(19.92, 6.40)X_i$	Normal
Gas	$CE_{2,2,2} = N(10.63, 1.38)X_i$	Normal
Power Supply	$CE_{2,2,3} = N(5.77, 3.88, 1.84)X_i$	Triangular
Expenses	$CE_{2,2,4} = N(26.09, 11.89, 7.53)X_i$	Triangular

Where X_i is the weight of the piece to be developed, which will have an allocation rate for the Cost according to the distribution that best fits the item.

Construction of $CTEP_3$ for the Tooling Manufacturing

The complementary activities for the time estimation of machining that help in the tool manufacturing process are the following [40]:

- *Habilitation of the material.* It consists of preparing the steel that will be machined by adjusting the shingles to have a reference cut for the machining; this activity lasts between 5 to 10 percent of the total machining activity.
- *Preparation of tools.* The tools that will be used in the machining operations are selected and prepared; this process lasts 5 to 10 percent of the machining activity.
- *Generation of operations.* The design of the tooling or device is executed according to the specifications and requirements of the client, then the designs are transformed into instructions for the operation of the CNC. The generation of operations is one of the main activities within the manufacture of tooling, and its duration lasts between 30 and 35 percent of machining activities.
- *Machining.* The design is emptied into the material, and a swarf is removed. This activity is carried out with numerical control equipment, which gives precision and certainty. This element gives added value to the manufacturing, so it is the guiding operation within the forecast model.
- *First Mold Assembly.* An initial assembly is carried out to see no interferences inside the cavity and the sealing is adjusted. This operation lasts no more than 2,880 min.

- *Heat treatment.* It is subjected to the cavity at high temperatures to subsequently cool it gradually; this allows the cavity to have a hardness on its surface; this operation lasts no more than 2,880 min compared to the standard established by the company.
- *Second mould assembly.* Once the cavities have been treated thermal, these are assembled again to verify if there are deformations or interferences inside the cavity. If these occur, they are readjusted and returned to verify the closure of the cavity, and this operation does not last more than 2,160 minutes for the standard set by the company.
- *First test run.* The die-cast mould is tested inside the die-cast equipment, allowing them to perform the necessary actions for the final adjustment. This operation does not last more than 1,440 min by the standard established by the company.
- *Final adjustment.* The adjustment of all the observations that were presented in the execution of the test is carried out. In general, these operations include the adjustment of the knobs and the adjustment in the closing of the mould; this operation does not last more than 2,880 minutes, according to the standard established by the company.

Defined the operations that make up the manufacturing of the injection mould, the times obtained from four documented projects are those described in supplementary file 9, where the different machining times are established and likewise, the relationship between the machining is sought, the weight and the number of cavities that make up the tool.

With these data, it is possible to identify the correlation between the weight removed against the weight of the mould (weight of the piece by the number of cavities) by applying the Pearson linear correlation index according to Eq. 13. Which establishes a correlation of 0.9369 and, subsequently, the correlation between the machining time required against the weight eliminated; with this value, it is possible to obtain the TEP$_{2,2}$ as follows:

$$TEP_{3,1} = \sum_{k \epsilon R_i} y_i^k T_k P_i = Y_i^k (705.00 + 161.75 P_i) \tag{13}$$

Where Y_i^k is a binary variable that takes the value of 1 if the activity is carried out, and 0 if the activity is not carried out, P_i which is then withdrawn weight given by $P_i = 0.252 + 155.98 X_i$, and X_i is the weight of the piece to be manufactured. For the estimation of the ECT$_{3,2}$, it is established that it is directly related to the time invested and the fixed and variable costs of the machining activity. The time costs are shown in the Table 2.

When the CTEP$_3$ has been developed for the activity of the manufacture of moulds, it is possible to use the model to forecast the Cost and time within the projects of die casting, as well as to measure its degree of precision.

Table 2 CNC hourly costs for the manufacture of injection molds

Cost per hour	Range in minutes	
	Min	Max
400	0	101663
250	101664	177352
200	177352	∞

4. Model accuracy

To determine the model's accuracy, the test of the χ^2 represented in Eq. 14 will be carried out to establish that the sample obeys the entity model for the estimation of Cost and time. Where V_0 is the real value, and V_e is the expected or predicted value, the k degrees of freedom are adjusted according to the number of observations generated for each test.

$$\chi^2_{(k-1)} = \sum_{k=1}^{N} \frac{(V_0(k) - V_e)^2}{V_e} \tag{14}$$

The test will be applied to each one of the developed sub-models of the CTEP, so the following elements will be evaluated:

- Cost of raw material.
- Cost of the piece.
- Time of manufacture of the piece.
- Tooling cost.
- Tool manufacturing time.

To determine the degree of precision when estimating the Cost of the raw material, a test with 19 degrees of freedom is applied, as shown in *supplementary file 10*. The obtained value of 5.4135 can be interpreted as a 95 % reliability of the model for the Cost of the raw material.

The same procedure follows the rest of the CTEP, which we can summarize in Table 3.

Table 3 Model sensitivity analysis

CTEP	Degree of freedom	χ2	Degree of Reliability (%)	Standard deviation	Kurtosis	Asymmetry	Jarque-Bera
Cost of raw material	19	5.4135	95	1.8213	0.2871	-0.0230	3.6807
Cost of the piece	19	12.1588	85	0.5015	0.0607	-0.0253	4.3209
Time of manufacture of the piece	19	12.9878	80	0.0248	-0.0376	-0.1643	4.6675
Tooling cost	5	2.2916	80	398.44	-1.2481	-0.0665	9.0323.
Tool manufacturing time	5	2.2857	80	0.2059	-1.1548	-0.0580	8.6379

5. Conclusion

The results obtained from the different tests carried out to determine the model's reliability show that it presents a degree of accuracy above 85 percent. This result allows a quick forecast to be made with the minimum information required for the quotation, leading to the construction of an entity-based model to efficiently determine costs and time to provide certainty and a competitive advantage to the die-casting industry.

Analyzing the model structure established that the information necessary for estimating Cost and time is introduced through the different entities built. Such analysis facilitates the person in charge of the quotation's fast and efficient handling of all the data required during the quotation process. These entities of Cost and time have in their main structures the Cost of the raw material, the Cost and time of manufacture of the tools, and the Cost and time of manufacture of the part. Such determination is an advantage in the process since it allows the evaluation of the different projects, although these represent other structures.

An important innovation that the use of CEP provided was that the model increases accuracy and facilitates user interaction. In the same way, it was possible to gather information to generate a solid and well-structured database on which the model can base its approximations.

Finally, in the development of future research, it would be possible to use other modeling systems, such as genetic algorithms or artificial intelligence, to increase the accuracy of the proposed model.

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