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Cost Estimation Tool for Metallic Parts Made by Casting: A Case Study

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Abstract: This work presents a mathematical tool to estimate the cost of fabricating pumps by traditional casting. The drivers that most affect the cost of the process are identified in each step of the procedure, i.e., material, labour, energy, tools and general expenses associated with any industrial activity. The mathematical expressions used for the calculation of the different cost drivers are presented and used to estimate the cost of fabricating the different parts composing a radial pump in a small Moroccan foundry. Therefore, the input data of the equations carefully consider the economic factors of this country. However, the developed tool is versatile and can be adapted to describe the casting process in other countries with different economies just by changing the input data accordingly. It is observed that the influence of the drivers in the final cost of the pump is very dependent on the number of pumps to be produced. In any case, the cost estimation tool presented in this work will allow for the optimization of the yield of the casting process rendering the involved company more reliable. The tool provides an idea of the implications of changing production factors, allowing the foundry to give accurate and fast responses without compromising its profits.

Keywords: sand casting; cost effectiveness; cost drivers; analytical-knowledge method

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1. Introduction

Casting is a manufacturing method by which molten metal is poured into a mould cavity that has a certain shape; upon solidification, the metal adopts the shape of the mould [1]. As the casting process has been present in human history for a very long time (and is, in fact, one of the oldest methods by which to obtain parts with a desired shape from materials that can melt), it has been deeply studied [2]. Such a broad use and long history means that casting products are present in most of the consumer goods used in everyday life. It is estimated that around 70% of all metal goods are produced using this processing method [3].

In the global market, competition grows every day and prices are becoming tighter, leaving little margin for profit. In this framework, in which reality changes quickly, having a tool by which to design the pieces facilitates the work, reducing the cost and the response time to the client [4]. A major part of the production expenditure (around 70%) of a piece is established in the design phase (materials and processes), which is simultaneously the phase for which the least amount of money is invested (about 7%) [5]. To enable cost reduction, tools that help estimate the cost of the parts in a reliable and easy-to-use way have to be developed.

Those tools/methods have as objective [6]:

- To generate budgets that avoid over or under-quoting that can result in the loss of company clients or even assume losses that endanger the viability of the company.
- To track the progress of external (labour rate, energy price and raw material cost) and internal factors (yield, recycling, rejection, and tools/methods used) and to evaluate their effect on the cost of the casting.

- To identify the drivers that might have a high impact on the cost reduction.

There are requirements of a very different nature, such as geometric or quality attributes associated with the demands of production that, beyond the requirements of the relevant materials, will also condition the subsequent processes (for example, melting and heat treatments). To optimize the final cost of the product, maximum attention must be placed on choosing the processes and materials that are most suited to the characteristics and conditions to be met by the final product.

To this end, product cost estimation (PCE) methods, based on different approaches, are used. It is difficult to classify the cost estimation methods as different authors have used different categories. For instance, Niazi et al. [7] divided the PCE methods into qualitative and quantitative categories, which are then subdivided into intuitive and analogical and parametric and analytical categories, respectively. In this case it can be difficult to fit one method into just one category, therefore, Hueber et al. suggested a more simplistic way to categorise them: analogous (analogical), parametric and bottom up (analytical) estimation techniques. The intuitive method, based on the knowledge and experience of an expert, is not repeatable by a third person, so it is not considered among the mentioned methods [8].

- Analogical techniques employ similarity with products found on historical databases by assuming that similar products have similar costs. They select certain variables, and a linear relationship is established between the product and the cost. These relations are then used to forecast the cost of the new product [9].
- Parametric methods apply statistical calculations by expressing cost as a function of its constituent variables. For this approach to be effective, the cost drivers have to be identified and the variance of data must be taken into account [7].
- In the bottom-up technique, estimation of the product is decomposed into the elementary tasks, operations and/or activities needed to perform the work. The costs involved in the process have to be characterised and classified and are usually known or easily calculated by means of algorithms and equations as they relate to the item's attributes, such as roughness or maximum thickness [10].

The results obtained using these tools are always a rough estimation of the real cost of the part. It is almost impossible to have all the information to give a 100% accurate value, as there are factors or elements that cannot be predicted and therefore cannot be considered.

The aim of this study is to estimate the cost of producing pumps by traditional casting in Morocco/North Africa. In this case, an analytical knowledge-based approach will be the method used and quantitative results will be sought. First, the drivers that most affect the cost of the mentioned process will be identified in each step of the procedure. Later, the mathematical expressions used for the calculation of the assessed value will be presented. Finally, a case study will be showcased to demonstrate the suitability of the tool.

The research methodology followed in this study is given in Figure 1.

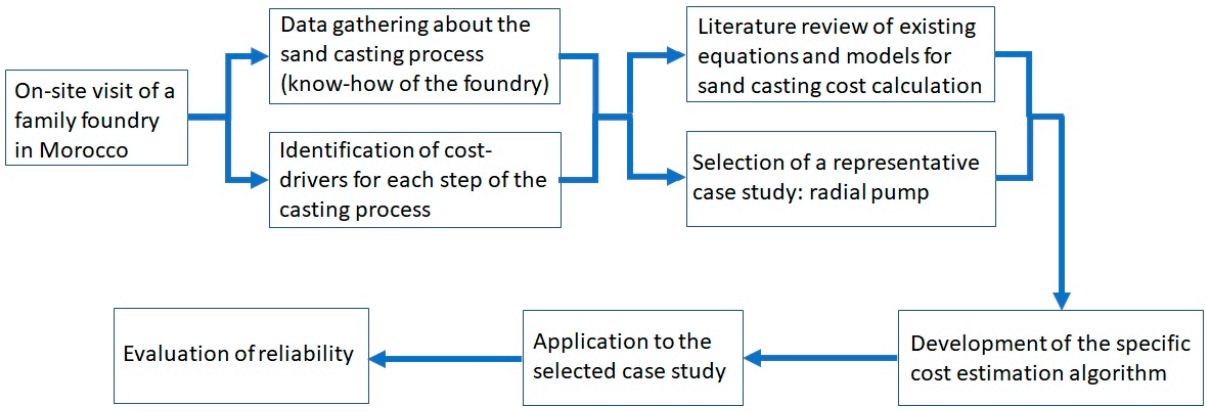

Figure 1. Schematic diagram of the research methodology followed.

2. Results and Discussion

2.1. Metal Casting Cost Drivers Assessment

The main factors that affect the final cost of the product in this case are material, labour, energy, tools and the general expenses associated with all industrial activity and that include furniture, administration and depreciation [11]. Studying the different steps of the casting operation will allow for a determination of the factors present in each phase. The overheads will not be mentioned since they are present during all operations and will be accounted as a percentage at the end of the calculations. The only mention of labour will occur when the difference between highly qualified and technical labour is taken into account. The remainder will be obviated as, together with the overheads, it is present throughout the entire activity.

To obtain a material by casting, the process follows three stages: pre-casting, casting and post-casting. Next, these steps will be deeply analysed.

2.1.1. Pre-Casting

The initial stage (before the production process starts) consists of the design of the mould and cores. This phase is highly sensitive and is directly related to the material used and the final shape of the part to be produced. The designer can either obtain a sample of the part to be reproduced or a document with detailed information (dimensions, volume, weight, materials density, thermal expansion coefficient, etc.) about the part. AutoCAD® (Autodesk, San Rafael, CA, USA), Solidworks® (Dassault Sytèmes, Paris, France) or similar software will be necessary to translate the part shape into the modelling tool. An adequate feeding/gating system should be designed to ensure a homogeneous filling of the mould, the cooling of the sample and dimensional stability. The gating system is responsible for leading the molten metal from the ladle to the mould cavity, ensuring smooth, uniform and complete filling while avoiding turbulence of the fluid, mould erosion, shrinkage, porosity and metal oxidation. Due to the complexity of the system, this step is performed by highly qualified professionals (an engineer or group of engineers) using specialised software such as MAGMASoft® (MAGMA®, Aachen, Germany), AutoCAST™ (3D Foundry Tech, Mumbai, Maharashtra, India), ProCAST (ESI group, Rungis, France), SolidCAST™ (Finite Solutions, Hamilton, OH, USA), etc.

Once the design of the mould and cores is finished, a pattern with the shape of the desired part has to be produced. The pattern is an approximate duplicate of the final casting part and is used to shape the sand moulds. The patterns are usually made of wood and are stored at the plant, so that they can be used many times to produce the same kind of sample. This step can be carried out with machines, or it can be handcrafted.

To create the mould, a mixture of sand, binder and activator has to be packed around the pattern in a flask (rigid metallic frame to hold the sand and the pattern). After waiting for the mixture to solidify (the time will depend on the chemicals used), the replica of the part has to be removed. This process is undertaken twice: one time for the bottom part (drag) and another time for the upper part (cope) of the pattern [12]. Any internal features of the casting that cannot be formed by the pattern are formed by separate cores (usually cores are made using different sand mixtures). The sand used for the moulds can be regenerated by thermal processing and can be valorised this way several times before it is discarded [13], reducing the amount of waste generated per cycle. The surfaces of the mould cavity have to be lubricated in order to facilitate removal of the casting product and to obtain a better surface finishing.

Once the two mould parts and the cores have been lubricated, they have to be put in place (forming something akin to a sandwich) and clamped. This step is important to prevent any metal loss.

Considering the above, the cost drivers related to the mould and cores design are labour (highly qualified) and tooling (specialised software). In the case of the mould and core preparation, all the drivers are present (labour, material, energy and tooling).

2.1.2. Casting

The metal must be melted at the temperature required by its chemical composition. This step is performed in different types of furnaces: cupola, induction, electric arc, reverberatory and crucible. The different heating methods have different efficiencies and material loss factors that must be taken into account when choosing the right device for the target material. The molten metal is kept at a set temperature in the furnace until everything is ready for its transfer to the mould. A refining step (slag removal) has to be carried out in order to avoid the production of gasses and chemical elements (sulphur or phosphorous) that could be detrimental for the cast material and produce defects, such as cracks and porosity, that will progressively deteriorate the mechanical properties [2]. Limestone, coke or dolomite are added for the protective slag formation [14].

The chemical composition desired for the casting part is usually achieved using scrap and virgin materials. The scrap can have external origin (leftovers of other manufacturing processes or end-of-life products) or internal origin (waste materials produced during casting such as gates, feeders, or faulty parts). Alloying elements in their pure form, or as alloys (i.e., ferroalloys or master alloys), are added to adjust the composition to the desired range.

The molten metal must be transferred to a pre-heated ladle, from which it will be poured to the mould. This step is performed as quickly as possible to avert premature solidification. Enough material must be poured in order to account for the gating and feeders and to ensure that after shrinkage there will be enough material for the part to be complete.

The cooling process will take different amounts of time depending on the geometry of the sample (wall thickness), the pouring temperature and the design of the feeding system. The solidification of the part is highly important as many defects, including shrinkage, cracks, or incomplete sections, can take place during cooling due to fast solidification [2]. Once the cooling is finished and the final shape is well established the cast part must be removed from the sand mould. This step is performed by the shake-out process and if there is still sand attached to the cast part, mainly in internal surfaces, other techniques that use pressurised air or shot-blasting are used.

At this stage, there is an excess of material that has solidified together with the cast (gating system, feeder, sprue, etc.). This material must be removed (fettling) by means of cutting or by breaking it away with hammers or special machinery. The material removed can be added to the melting furnace and reused, reducing the amount of waste and thus the cost of the part.

Regarding the cost drivers present in these steps, material is present in the first part (melting, refining and composition adjustment) while the second part involves the tooling (filling, shake out and fettling). The casting step is the most energy demanding due to the melting process carried out in the furnace. The shake-out and fettling will also require energy and the melting will need to utilize some tooling, including the use of the furnace and the specialised tools that must be used in order to work at such high temperatures, but these are secondary compared with the energy demands of the melting process.

2.1.3. Post-Casting

Post-casting involves heat treatment processes and finishing of the cast parts.

- Heat treatments (HT)

Heat treatments are one of the most expensive post-casting operations, since they are primarily performed at high temperatures. Heat treatments are a group of industrial and metalworking techniques used to alter the physical properties (ductility, malleability and hardness) of the materials. Metals in the solid state are subjected to heating and cooling processes, in order to obtain materials that are more versatile and are tailor-made to fulfil the desired working conditions of the parts. Heat treatment processes include

annealing [15], quenching [16], tempering, cryogenic treatment [17], decarburising and nitriding [18].

- Finishing

Although near-net shape samples are obtained with the casting method, some machining will be needed to achieve the desired dimensional accuracy and surface finish to comply with the tolerances imposed by the customer. This step is essential in the case of parts that will be assembled with other parts.

To reach tight dimensional control, machining is used. It is desirable that the piece to be machined has high machinability. This is related to several factors such as resistance to cutting, expected tool life, the attainable surface finish quality, degree of dimensional control, sensitivity to changes in cutting conditions (speed, cutting depth, feed etc.), or force and energy required.

There are several types of machining that will be needed depending on the shape and size of the sample, these include single point methods (turning, planning or shaping) and multiple point methods (drilling, milling and grinding).

Once the samples are ready, they must be assembled and inspected to see if they fulfil the specifications of the customer.

In the post-casting there is no material involved. In this case, there is a high consumption of energy mainly due to the heat treatments and the machining performed. The need for tooling is also present in all the steps, with a greater emphasis on the machining part.

A diagram indicating the cost drivers assigned to each process is given in Figure 2.

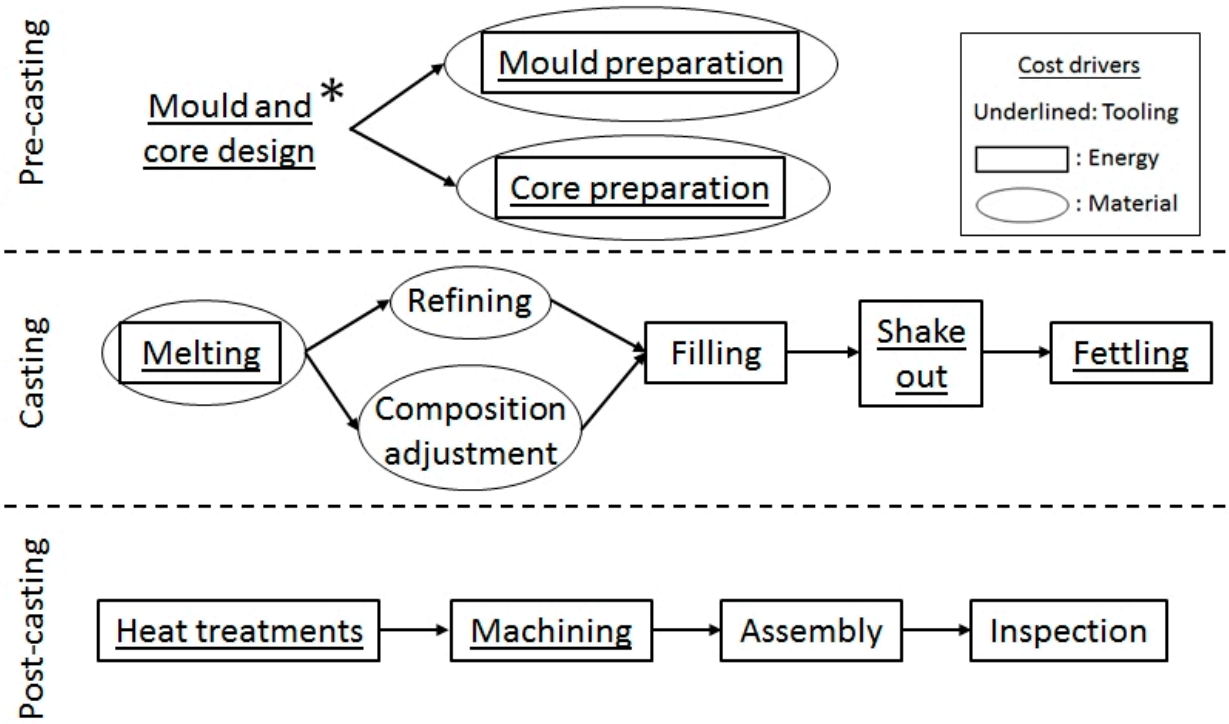

Figure 2. Casting process schematic diagram explaining the cost drivers involved in each step. * Highly qualified labour involved.

As in any other type of activity, in a foundry there are some costs derived from activities that are not directly linked to the casting process (non-manufacturing related operations) but are necessary to run a business, including marketing campaigns, travel fees, executive salaries, legal services, etc. All of these expenses will be considered together as administrative costs. On the other hand, there also exists depreciation of the machinery, of installations (i.e., office, cars or land), etc. Depreciation caused by obsolescence, wear,

exhaustion, etc., will be named as depreciation cost and will be taken into account together with the administrative expenses as overheads. This last item for the calculation of the total cost of the cast part will be accounted as a percentage based on the cost of the rest of the cost drivers involved and, unlike the remaining drivers, will not be calculated using formulae.

Once the basics of the casting process have been examined, the equations and calculations used for the cost study will be presented in Section 2.2.

2.2. Mathematical Expressions for Calculating the Cost

The total cost of the cast part is calculated using the following Equation (1) [11]:

$$C_{total} = C_{material} + C_{labour} + C_{energy} + C_{tooling} + C_{overheads} \quad (1)$$

2.2.1. Material

The cost associated to the material part is calculated using Equation (2) [11].

$$C_{material} = C_{direct} + C_{indirect} \quad (2)$$

where:

$$C_{direct} \text{ is the direct material cost} = P_{metal} \times W_{cast} \times f_m \times f_p \quad (3)$$

modified from [11].

P_{metal} = price of the metal used in MAD/kg
W_{cast} = weight of the cast part in kg
f_m = metal loss factor during melting (1.01–1.12) *
f_p = metal loss factor during pouring (1.01–1.07) *

$$C_{indirect} \text{ is the indirect material cost} = C_{mould\ sand} + C_{core\ sand} + C_{miscellaneous} \quad (4)$$

$$C_{mould\ sand} \text{ is the mould sand mixture (with activator and binder) cost} = P_{mould\ sand} \times f_{recycle} \times f_r \times f_{mould\ rej} \times W_{mould\ sand} \quad (5)$$

modified from [11].
Where:
$P_{mould\ sand}$ = price of mould sand mixture MAD/kg *
$f_{recycle}$ = sand recycling factor (0.1–1.0) *
f_r = casting rejection factor (1–1.12) *
$f_{mould\ rej}$ = mould rejection factor (1–1.10)

$$W_{mould\ sand} \text{ is the weight of sand mould in kg} = \rho_{mould\ sand} \times V_{mould\ sand} \quad (6)$$

$\rho_{mould\ sand}$ = mould sand density in kg/m^3

$$V_{mould\ sand} \text{ is the total volume of the mould sand in m}^3 = V_{flask} - V_{cast} - V_{gating} - V_{feeder} - V_{core} \quad (7)$$

$V_{mould\ sand}$ = total volume of the mould sand in m^3
V_{flask} = volume of the flask in m^3
V_{cast} = volume of the cast part in m^3
V_{gating} = volume of the entire gating system in m^3
V_{feeder} = volume of feeders in m^3
V_{core} = volume of the core(s) in m^3

$$C_{core\ sand} \text{ is the core sand mixture (with activator and binder) cost} = P_{core\ sand} \times f_{recycle} \times f_r \times f_{core\ rej} \times W_{core\ sand} \quad (8)$$

$P_{core\ sand}$ = price of core sand mixture MAD/kg *

$$W_{core\ sand} \text{ is the weight of sand mould in kg} = \rho_{core\ sand} \times V_{core\ sand} \quad (9)$$

$\rho_{core\ sand}$ = core sand density in kg/m^3
$V_{core\ sand}$ = total volume of the core sand in m^3
$f_{core\ rej}$ = core rejection factor (1–1.10)
$C_{miscellaneous}$ = miscellaneous materials cost—coatings, lubricants, blasting media, wood (for pattern)

$$C_{wood} \text{ is the wood cost for pattern} = P_{wood} \times V_{wood} \quad (10)$$

P_{wood} = price of wood in MAD/m^3
V_{wood} = volume of wood used to produce the pattern in m^3
* These values are found in [11].

2.2.2. Labour

The cost related to labour is calculated by Equation (11).

$$C_{labour} = C_{labour\ highly\ qualified} + C_{labour\ technical} \quad (11)$$

where:

$$C_{labour\ highly\ qualified} \text{ is highly qualified labour cost} = f_r \times (\sum m\ f_{design\ rejection} \times S_{high\ qualification} \times l_{design\ HQ} \times t_{design})/n_{parts} \quad (12)$$

modified from [11].
f_r = factor for casting rejection (depends on the material and the tolerances) (1–1.12) *
m = number of designs
$f_{design\ rejection}$ = rejection factor for the design (1–1.2)
$S_{high\ qualification}$ = salary per hour of the highly qualified worker
$l_{designHQ}$ = number of highly qualified workers involved in the design
t_{design} = time spent in the design in h
n_{parts} = number of parts produced from the design/activity

$$C_{labour\ technical} \text{ is the technical labour cost} = f_r \times (\sum n\ f_{activity\ rejection} \times S_{technical} \times l_{activity} \times t_{activity})/n_{parts} \quad (13)$$

modified from [11].
$f_{activity\ rejection}$ = rejection factor for activity i: $f_{core\ rejection}$ = 1.0–1.2; $f_{mould\ rejection}$ = 1.0–1.1; $f_{activity\ rejection}$ = 1 for other activities *
n = number of activities
$S_{technical}$ = salary per hour of the technician
$l_{activity}$ = number of technicians involved in certain activity
$t_{activity}$ = time spent in certain activity in h

2.2.3. Energy

The calculation of the energy cost is considered by means of Equation (14).

$$C_{energy} = C_{melting} + C_{holding} + C_{heat\ treatments} + C_{machining} + C_{other\ energy} \quad (14)$$

where:

$$C_{melting} \text{ is the cost of the melting process} = P_{energy} \times E_{melting} \times W_{metal}/\text{units per batch} \quad (15)$$

P_{energy} = price of the energy in MAD/kWh

$E_{melting}$ is the energy required by the electric arc furnace for melting the metal in kWh/t metal

W_{metal} = weight of metal needed (including 30% extra for the feeder and gating system) in tonnes

$$C_{holding} \text{ is the cost of holding the material at a certain temperature} = P_{energy} \times E_{holding} \times t_{holding} \times w_{metal}/\text{units per batch} \quad (16)$$

$t_{holding}$ = time that the holding process takes in min

$E_{holding}$ is the energy required to keep the temperature of the melt constant during holding time kWh/t per min

➢ $C_{heat\ treatments}$ = the cost of the heat treatments:

$$C_{stress\ relieving} = P_{energy} \times E_{stress\ relieving}/\text{units per batch} \quad (17)$$

$E_{stress\ relieving}$ = the energy required for stress relieving in kWh per batch

$$C_{annealing} = P_{energy} \times E_{annealing}/\text{units per batch} \quad (18)$$

$E_{annealing}$ = the energy required for annealing in kWh per batch

$$C_{preheating\ and\ cooling} = P_{energy} \times E_{preheating\ and\ cooling}/\text{units per batch} \quad (19)$$

$E_{preheating\ and\ cooling}$ = the energy required for preheating and cooling in kWh per batch

➢ $C_{machining}$ is the energy required for machining the metallic part:

$C_{machining\ pp}$ = the cost of the machining process per part = $P_{energy} \times E_{machining} \times t_{machining}$ (20)

$E_{machining}$ = the energy required to machine a part in kWh

$t_{machining}$ = the time required to machine the part in h

➢ $C_{other\ energy}$ = the cost of the other energy used for running the plant

Most of the processes mentioned (melting, holding and HT) produce several parts at the same time while others, such as machining produce individual parts, therefore, the processes that obtain several parts per batch will be divided by the number of parts processed.

2.2.4. Tooling

The cost involving tooling is taken into account using Equation (21).

$$C_{tooling} = C_{updates} + C_{consumables} + C_{maintenance} + C_{machining} \quad (21)$$

where:

➢ $C_{updates}$ = cost of software updates

$$C_{updates} = \Sigma^{nup}\ P_{updates}/n_x \quad (22)$$

n_{up} = number of updates

$P_{updates}$ = price of software updates

n_x = amount of design, machined parts, etc. produced

➢ $C_{consumables}$ = the cost associated to consumables for the use of tooling in MAD
➢ $C_{maintenance}$ = the cost of the equipment maintenance in MAD
➢ $C_{machining}$ = the cost of machining in MAD per part **

** will depend on surface roughness (3.2–50 μm Ra for sand casting) and dimensional tolerance.

2.2.5. Overheads

The expenses related to overheads are calculated using Equation (23) [11].

$$C_{overheads} = C_{administration} + C_{depreciation} \quad (23)$$

where:

- $C_{administration}$ = the administration of the whole business in % of the cast part cost.
- $C_{depreciation}$ = the depreciation cost of the entire plant in % of the cast part cost.

2.3. Case Study: Casting a Radial Pump in Morocco

The diagram of the radial pump to be produced by casting is given in Figure 3. The real photo of the pump produced in a Moroccan local foundry is given in Figure 4.

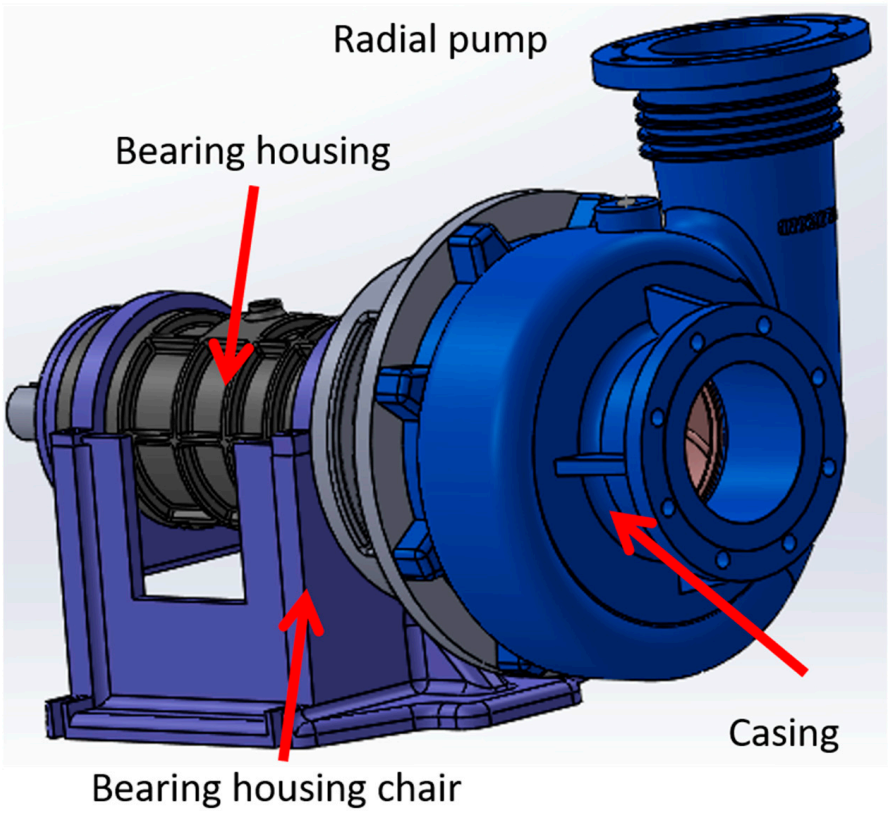

Figure 3. CAD model of the radial pump parts.

More detailed images of the internal parts of the pump are given in Figures 5 and 6.

Some of the items (mechanical sealing, bearings and the lock nut for the washer) highlighted on Figures 4–6 are not produced locally but bought on the international market.

The hydraulic part, that is in contact with the liquid, consists of the impeller, the back casing and the casing. The hydraulic part is made of 30% Cr cast iron.

The mechanic part consists of the shaft, bearing housing chair, bearing housing and lid. The shaft is made of stainless steel (316) while the bearing house, the bearing housing chair and the lid are made of grey cast iron.

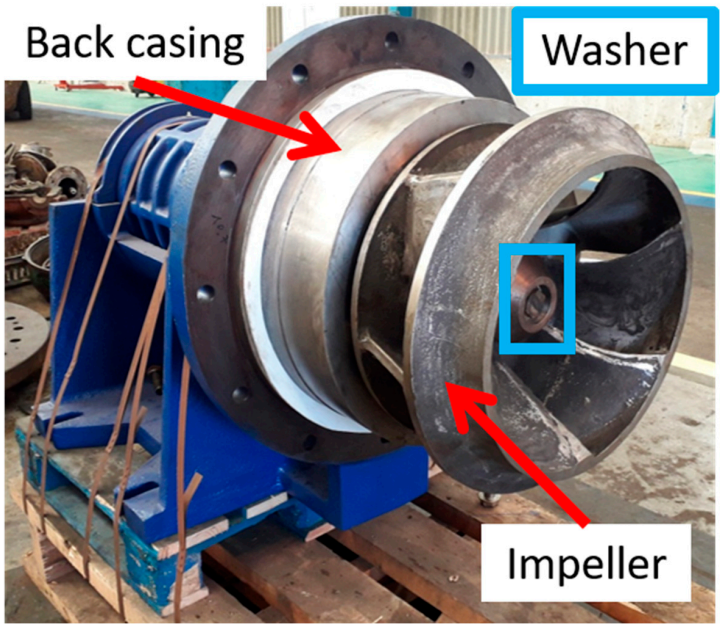

Figure 4. Photo of radial pump cast in a Moroccan foundry.

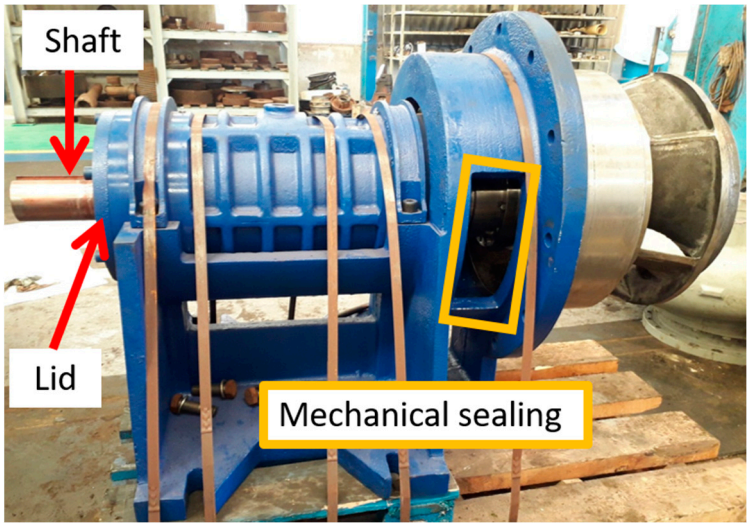

Figure 5. Picture of the rest of the parts produced locally.

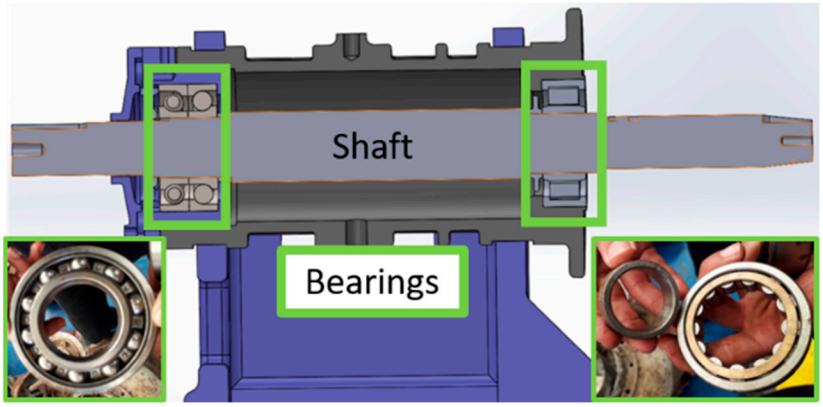

Figure 6. CAD diagram and photos of parts that are bought overseas.

2.3.1. Cost Estimation Input for Metal Casting

To conduct an estimation of the costs of the casting parts and apply the aforementioned formulae (Section 2.2) for their calculation, input data are essential. Some important information, such as the weight of the parts, their volume, tolerances, etc. must be given by the product designer, while other specific values, such as the manpower used in each activity, the melting time or the type of sand mixture used, must be provided by the foundry in which those processes are carried out. In this case study, some information was gathered during a local foundry site visit. Nevertheless, when there are no values available from the Moroccan ecosystem, a range based on the literature was used.

Material

Regarding the direct material used (the material that will be present in the pump), its cost contribution will depend on many factors. Historically, metals have been divided into different groups depending on their value; inexpensive (base metal) vs. noble metals that show better behaviour against oxidation or corrosion. A more detailed classification is given below [19].

- Very-high price (50-year average ~$1000/mole): Au, Sc and platinum group metals (Ru, Os, Rh, Ir, Pd and Pt).
- High price (50-year average ~$100/mole): Ag, Ga, Ge, Hf, In, La, Ta.
- Intermediate price (50-year average ~$5/mole): Be, Bi, Cd, Co, Mo, Nb, Sn, Te, W, Y and Zr.
- Low price (50-year average ~$0.5/mole): Al, Cr, Cu, Fe, Li, Mg, Mn, Ni, Pb, Sb, Si, Ti, V and Zn.

However, in these uncertain times, in which, due to the COVID-19 outbreak and the war in Europe, the supply of raw materials is not always guaranteed or can suffer significant delays, the cost can vary enormously. On the one side, the origin of the raw material will be an important factor to consider, meaning that locally available materials will be sought to assure availability and avoid transport issues (related to time loss in customs, etc.). Morocco does not have a metallurgical industry such that it can ensure enough scrap to produce large quantities of parts in a continuous manner over time. Therefore, the scrap used in this work was imported from the international market, especially the European market, and the cost will be calculated using international value estimations. On the other hand, the offer and demand of the material will be an issue that cannot be avoided as it is out of the control of the producer. However, it can be minimised by being attentive to the metal market prices and trying to stock when the prices are optimal.

The indirect material is that which, while not present on the cast part, is nonetheless necessary to produce it. The main contributors are the sand that will be used to cast the material and the miscellaneous materials that comprise the remaining materials used. During the mould preparation process, small amounts of coating products, metalizing paints, lubricants, etc. are employed, but the amount per cast part is so small that, when compared with other miscellaneous materials, such as the wood for the pattern, their value is deemed to be negligible. This is why, in the case of miscellaneous material, only the wood will be considered. The wooden pattern is prepared in either white or red wood (pine or mahogany), depending on the amount of cast parts to be produced. In this case, pine wood was chosen due to the small production demand and cost balance.

The main defects that generally occur on the cast part and which lead to its rejection have different sources, including human, material, method and machine [20]. Among the most common defects, those associated with the mould sand (size and composition) and gating system (feeding velocity, temperature, etc.) are primarily responsible for the rejection. Therefore, it is of upmost importance to choose a sand mixture that has a proper balance of grain size, permeability, moisture content and green hardness to avoid problems that include bad surface finish, sand inclusion, entrapped air and gas (that lead to porosity), washing of the sand, etc [21]. In this case study, the sand used for the mould is a silica

sand with 1.5 wt.% of no-bake organic furanic resin with a catalyser (Zircon, manganese or graphite) while in the case of the core, the sand is a Carbofen® natural resin with its catalyser (manufacturer recommended dosing).

The values of the densities of the mould and core sands were estimated to be 1800–2400 kg/m^3 according to data found in the literature [22]. The different values used for estimating the cost allocated to the material part of the pump are given in Table 1.

Table 1. Values used for the cost estimation with references.

Material	Price	Price MAD (Exchange Rate of 31 December 2022)	Reference
Scrap grey cast iron	26–41.5 INR/kg	3.28–5.236 MAD/kg	[23] (accessed December 2022)
316L Stainless steel bar	6148–7783 $/T	64.21–81.29 MAD/kg	[24] (accessed December 2022)
FeCr (65% Cr min.)	6.74–9.22 €/kg Cr	75.37–103.09 MAD/kg Cr	[25] (accessed December 2022)
Mould sand	1.2 INR/kg	0.15 MAD/kg	[11]
Core sand	3.0 INR/kg	0.38 MAD/kg	[11]
Pine wood	700–900 INR/ft^3	3120–4012 MAD/m^3	[26] (accessed December 2022)

Labour

In this case, the workforce was divided into highly qualified and technical. In most of the processes that are carried out in the foundry it is necessary to have basic knowledge and skills in handling either the equipment used, or the techniques put into practice. However, some of these activities are repetitive and do not need a lot of experience to handle them, so we consider these skills as technical. This group includes the people involved in material movement, furnace control and management, mould preparers, machining operators, etc.

On the other hand, there are more complicated calculations, in which, due to the need to use more sophisticated tools—such as computer modelling programs, complex mathematical calculations, deep knowledge of the nature of the material, etc—the requirements are of a higher level. In general, to carry out this type of work, formal training is required. Therefore, production engineers, laboratory staff, etc. are considered to be part of the highly qualified labour group.

The design of the gating system for the mould is the most difficult part of the entire process, so great attention must be paid, and highly qualified workers are needed. The pouring rate, which is dependent on critical casting thickness, metal fluidity and friction, must be carefully analysed to avoid hot spots or cold shuts. Other factors, such as the number, diameter and location of the risers, the pouring temperature and the sprue dimensions will also affect the solidification of the metal and hence the rejection rate of the cast parts. The rejection factor for the design part is calculated from the average of the values reported by Desai et al. [20]. In this case, a group of four engineers (product, tooling and foundry engineers, quality inspectors and managers) were involved in the process. This process will take at least a week, working first with AutoCAD® (Autodesk, San Rafael, CA, USA) and then with MAGMASoft® (MAGMA®, Aachen, Germany) software to develop the first design. Usually, several trials are needed to reach the correct system and this part is refined by trial and error. The cast part volume and weight are inputs that are obtained from the CAD design.

Salary for a highly qualified individual in Morocco is estimated to be around 12.000 MAD/month or 60–65 MAD/h while the technician salary is around 5.000 MAD/month or 25–30 MAD/h.

The fabrication of the wood pattern can be done manually or automatically in machining equipment. Working manually is time consuming, as the preparation of intricate shapes takes eight operators about a week, whereas use of the machining equipment reduces this to one working day for two operators. The latter will be the chosen assumption to calculate the cost.

The sand mixtures were carried out for 24 h. As this is a continuous process and it is performed automatically, the labour cost can be neglected [11].

The mould preparation has many steps to follow [27], including addition of metalizing paint to help demoulding, good dispersion of the sand and filling of the mould, solidification before removing the wooden pattern, treatment of the mould with fire to ensure a smooth surface, accurate positioning of the drag and cope to avoid lost metal, etc. Hence, two operators are involved in the process for 1.5 h. The sizes of the flasks to prepare the moulds are as follows (by increasing size):

- $0.5 \times 0.5 \times 0.5$ m^3
- $0.5 \times 0.5 \times 1$ m^3
- $0.75 \times 0.75 \times 0.5$ m^3
- $1 \times 1 \times 0.5$ m^3
- $1 \times 1 \times 1$ m^3

The casting process itself is divided into the set-up of the furnace, the melting and composition adjustment of the metal and the transfer and pouring into the moulds. The first step, the set-up, takes about 1 h and involves placing the scrap material and ensuring the furnace is ready. During the melting of the metal (about 1 h) one operator refines it by removing impurities in the form of slag and thereby reducing the inclusions, at the same time the operator takes samples to determine if the composition is the desired one or not (measurement is performed using an atomic emission spectrometer). The final step (pouring into the mould) must be carried out quickly (15 min) to avoid the cooling of the molten metal; thus, the metal is first transferred to a pre-heated crucible from where it will be poured into the sand moulds.

To obtain the proper part size, the shrinkage of the cast metal has to be taken into account. There are two kinds of shrinkage. Firstly, there is solidification shrinkage. This takes place because the liquid has a smaller density than the solid and to avoid its effect (porosity, cavities, etc.), risers and chills must be used, providing a continuous molten metal supply. Secondly, as the part cools down, there is a shrinkage related to its thermal contraction. The shrinkage depends on the material, the wall thickness, the complexity of the shape and the cooling rate and is very difficult to estimate [28]; therefore, the know-how of the foundry is drawn upon to take it into account. In this case both will be accounted together as 9 vol.%. The cooling down of the sample takes about 24 h inside the mould to avoid the distortion of the part.

The shake out and fettling step takes only few minutes (15 min) in specialised equipment managed by an operator. The sand that has been used is recovered and transferred to the plant where it will be recycled several times by thermal treatments before it is considered to be spent sand. This spent sand is a waste product of the foundry but has received much attention as a sand replacement in other industries such as construction [29].

Energy

The energy consumption of foundries is very high due to the high temperatures needed to work (melt and tap) the metals and because the machining process is the most energy demanding and least effective manufacturing process [30]. Therefore, there has lately been a large effort to increase the energetic efficacy of all the processes involved in the production of parts, to enhance economic and environmental functioning while enhancing competitiveness. The electricity price used in this work was of around 1.6 MAD/kWh, [31] for high energy consumption rate during peak hours.

There are many types of furnaces to melt and prepare the metal for casting. In this study, an electric arc furnace was used. The induction furnaces lose heat from the vessel and inductor and show inefficiencies in the interactions between the electromagnetic field and the material.

These furnaces have very different energy consumptions (depending on their efficacy, isolation, etc.) therefore, in order to perform an accurate estimation, several values found in the literature were averaged—580 kWh/t steel:583 kWh/t liquid [32], 300–550 kWh/t

steel [33], 570–1000 kWh/tonne (melt) [34] and 350–700 kWh/tonne of steel [35]. This energy is used to raise the temperature from around 25 °C to the melting temperature (in the order of 1500 °C) and then to melt the metal at a constant tempererature until all the material is in a liquid phase. Some over heating is also provided to account for the heat losses during tapping and to avoid premature cooling. The melt is kept at this temperature (holding) until the rest of the equipment and labour are prepared for the tapping step. During this time, the energy consumption is assumed to be 0.4 kWh/t per min [32].

In this work, thermal processes alone will be studied, rather than thermo-chemical. The most common heat treatments applied to grey cast irons are stress relieving and annealing [36]. Stress relieving is usually performed at 550–650 °C for about 1.5 h per 25 mm^2 cross sectional area until it is slowly cooled down. On the other hand, annealing can be performed for several reasons, including ferritizing, graphitizing, etc. In this case generic treatment conditions (800–950 °C for 2.5 h) were chosen to calculate the necessary energy [37]. The cooling must be performed in a controlled manner inside a furnace and the energy needed for both cooling and preheating of the furnaces will be accounted together as 33 kWh per batch.

In the case of high chromium cast iron, the heat treatment performed is annealing, which softens the material and improves its machinability. In this case, the conditions used are 700–750 °C for 6 h [38].

When studying the energy requirements of the machining step, several authors have agreed that the actual specific cutting energy is only a fraction of the total energy demanded to carry out processes such as workpiece handling equipment, cutting fluid handling equipment, chip handling equipment, tool changers, computers, and machine lubrication pumps [39,40]. Therefore, a large part of the energy necessary to run the equipment is independent of the types of metals, of the hardnesses, cutting speeds, etc. as it is mainly concerned with the time the machine is powered on (idle time) [41]. Dahmus et al. analysed the impact of the cutting energy on the total energy demand of the process and saw large differences from a 48.1% contribution in the case of an automated milling machine to 69.4% for a manual machine [39]. Considering the values gathered by Balogun et al. [41] in their review and the ones reported by Dahmus et al. [39] an average value of 40% will be used. The value used for calculating the energy requirement for the machining of steel parts (0.407 kWh) [41] was estimated as the average of the experimental values obtained for the machining of a 316 L stainless steel part. Gutowski et al. [34] studied the specific energy needed for machining different kinds of materials. The average of the values (Table 2) reported in their work was used to calculate the total energy required for machining parts made of different materials.

Table 2. Energy requirements for machining processes.

Material	Specific Energy Range (kJ)	Average Specific Energy (kWh)
Stainless steel	250–625	0.1215
Steel	260–1150	0.1958
Cast iron	140–690	0.1152

In general, all furnaces have a low efficiency value which is set in this work to 40%. On top of that, there are furnaces that are kept on during holiday periods or weekends due to the high energy demand needed to start them again and to reach the needed temperature [34].

Running an industrial facility has, together with the energy related to the specific activity, an energy requirement similar to any building using light, air conditioning, computers, etc. That energy requirement was taken into account as part of the "other energy" factor.

Tooling

The software for simulating the cast process is expensive compared with the one used for the design of the part (AutoCAD® (Autodesk, San Rafael, CA, USA), Solidworks® (Dassault Sytèmes, Paris, France), have an average 1500 USD annual subscription. The price will depend on the different features needed and the supplier. For instance, the cost of MAGMASoft® (MAGMA®, Aachen, Germany) is 3000 USD/month but if other packages are needed to allow the calculations of the feeder, gating, riser, porosity, etc. then SolidCAST (17.5k USD), FlowCAST (8k USD), WinCAST (18k USD), etc. should be added to that price. Therefore, the cost of the software will vary enormously depending on the need of the designer. The software companies usually give a tailor-made quotation depending on the use, country of origin, if it is for educational purposes, etc. In this case, an estimated cost value of 50k USD/year is used.

Machining is performed using a computer numerical control (CNC) machine. This piece of equipment is programmed to guide the tools and do the tool change automatically (reducing the set-up time) to shape the component accordingly. The one used in this work (DMV 160 FD duo block DMG Mori Deckel Maho 5 axis 64 tools) needs only one minute to change tools and set up. The software used for these machines (example: OneCNC) has no maintenance cost. This piece of equipment uses different tools depending on the type of cutting that will be performed. For instance, in the case of the turning and milling operations, high speed steel or tungsten carbide inserts are used. The tool life is affected by several parameters such as speed, cut of depth, surface finish, etc. and is, therefore, impossible to predict with theoretical formulae so that empirical approximations should be used instead [42]. The average cost of machining is around 40 USD (370 MAD) per hour. The machine needs about three days (working 8 hours a day) to finish machining the entire pump. In this cost, the consumable and maintenance costs together with the tools used (inserts) are considered.

Overheads

In this part, the non-manufacturing related expenses are taken into account. The cost related to the depreciation of a casting plant is around 20% [43]. This value does not consider the specialised equipment used for all of the steps of the casting process (furnaces, CMC machines, etc.) that have already been analysed but the depreciation cost of the general use software and hardware, transportation facilities, office furniture and all the elements present on any commercial activity. A 10% value will also be considered to account for the administrative costs that imply marketing, accountancy, communication, travelling, legal services, sales office, shipping, insurance, etc.

3. Final Cost and Remarks

As mentioned in Section 2.3. the analysed pump is made up of several pieces that must be cast separately and assembled at the end. No multi-cavity casting was used due to the large size and complex shape of the parts. Therefore, the cost estimation shall be calculated for each piece and then added together for the estimation of the final cost. In this case, an Excel (Microsoft®, Redmond, WA, USA) workbook was used wherein each part of the pump (impeller, casing, back casing, shaft, bearing house, bearing house chair and lid) had its own sheet in which material, labour and energy were analysed. Tooling was accounted for the entirety of the pump at once and was therefore calculated in a separate Excel sheet. Because overheads were calculated as a percentage, this calculation was carried out in the last step just before obtaining the contribution of each driver to the final cost.

The overall cost is divided into the manufacturing-related expenses, which are material, labour, energy and tooling, and the non-manufacturing-related expenses, or overheads. The summation symbol is added to emphasize the fact that each part of the pump has its own contribution to the different drivers.

Manufacturing-related activities:

$\sum C_{material}$ hydraulic part (impeller, casing and back casing) + mechanic part (shaft, bearing house, bearing house chair, lid)

$$C_{materia\,l} = C_{direct}\ (30\%\ Cr\ cast\ iron) + C_{indirect}\ (mould\ sand + core\ sand + wood)\ for\ impeller, casing\ and\ back\ casing \quad (24)$$

$$C_{material} = C_{direct}\ (316\ SS) + C_{indirect}\ (mould\ sand + wood)\ for\ shaft \quad (25)$$

$$C_{material} = C_{direct}\ (Grey\ cast\ iron) + C_{indirect}\ (mould\ sand + wood)\ for\ lid \quad (26)$$

$$C_{material} = C_{direct}\ (Grey\ cast\ iron) + C_{indirect}\ (mould\ sand + core\ sand + wood)\ for\ bearing\ house\ and\ bearing\ house \quad (27)$$

$$\sum C_{labou\,r} = \sum C_{highly\ qualified} + \sum C_{technical} \quad (28)$$

$$\sum C_{energy} = C_{melting} + C_{holding} + C_{heat\ treatments} + C_{machining} + C_{other\ energy} \quad (29)$$

$$C_{tooling} = C_{updates} + C_{machining} \quad (30)$$

$C_{overheads}$ = 30% of manufacturing related activities cost

$$C_{total} = \sum C_{material} + \sum C_{labour} + \sum C_{energy} + C_{tooling} + C_{overheads} \quad (31)$$

After using the equations and approximations explained in this work, the total calculated cost of the pump amounts to approximately 80.000–85.000 MAD. The allocation of cost of the different cost drivers analysed on the total value is given in Figure 7.

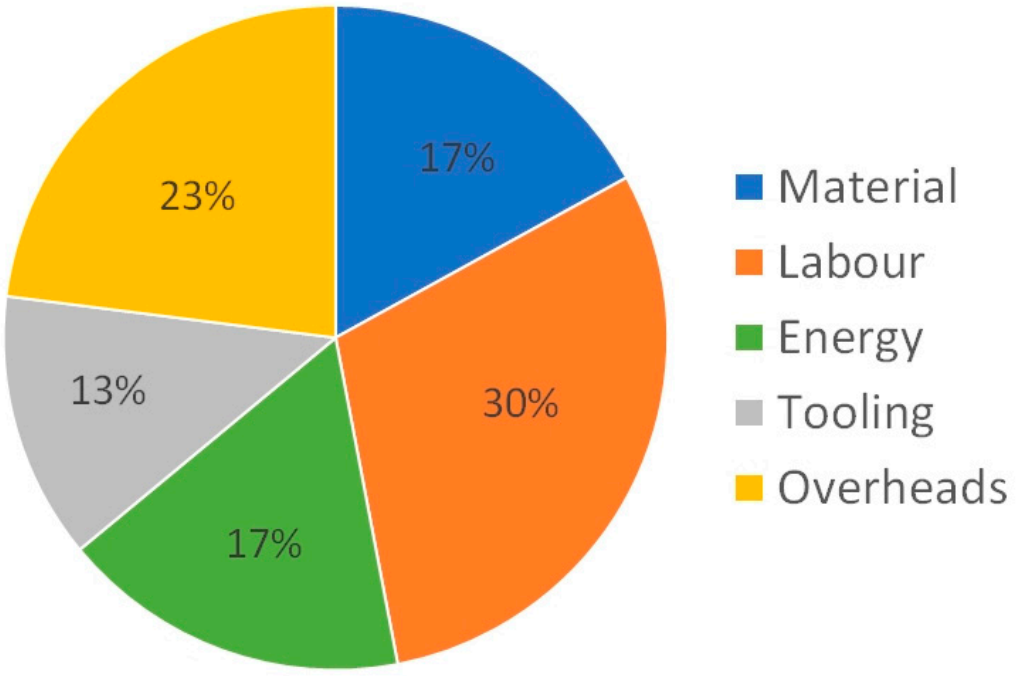

Figure 7. Contribution of the different cost drivers to the total cost.

As can be seen from the results, the highest cost is that related to labour. Although in Morocco manpower is not as expensive as in its neighbouring European countries, the contribution of labour to the final cost is higher than expected and is related to the fact that the study is focused on a small foundry in which many processes are carried out manually instead of with automated equipment that would save costs in terms of time and wage bills. Even if the first capital investment to obtain this kind of automated equipment is very high and not always possible for a family run business, in the long term it could save a lot of costs and be more efficient. This effect is not only clear in terms of direct costs, such

as reducing the time and number of operators, but also in terms of eliminating human error in the activity. This would result in other savings, such as material and energy, while creating a stronger ability to answer the questions of clients, in turn generating an increase in confidence.

Regarding the calculation of overheads, it must be taken into account that in a family run business much of the time administration expenses are reduced to a minimum as, instead of employing more people, many of these activities are carried out by workers in addition to their usual activity. In this work, a 10% value was used. When it comes to the depreciation of the foundry, a value of 20% was found in the literature but this is probably an overestimation. Nevertheless, it is important to raise awareness of the share of the non-manufacturing related operations, as those go unnoticed, though in reality they are unavoidable and contribute considerably to any activity carried out in an industrial setting. When special custom-made parts have to be produced, the production volume is typically smaller. This is due to the inaccuracies, rejections, etc. that must be overcome until the best gating system and design are found. Therefore, although many expenses continue to be the same, there may be less produced goods to pay back costs associated with administration and depreciation, this in turn increases the percentage of overheads. Once the production is scaled up to higher volumes, the turnover increases as well and those costs will be reduced.

The energy expenses in the metallurgy industry are always very high, due to the high energy requirements of the metal melting, heat treatments, etc., it is therefore not surprising to perceive this to be the third primary cost. In such activities, it is difficult to reduce the energy demand, however, there are special electricity rates for time slots in which the price per kW is lower and when the most energetically demanding activity should be carried out. Planning the activities to reduce the holding time—the idle time when the furnace is on without material, etc.—could make a difference and reduce this part of the monthly bill. Another option could be to try to reduce the heat lost during the process (mainly from the furnace) by working on improved isolated equipment or to store that lost energy and use it in other processes, such as heat treatments.

The percentage awarded to the material represents, as expected, a significant part of the final cost. It has to be taken into account that, as previously mentioned, Morocco is not a country with a strong metallurgical industry, so local scrap sources are not enough to ensure a regular supply. Having said this, it is necessary to underline the fact that, in general, the calculations have been carried out taking into account the price of the scrap and not of the pure raw material. Therefore, a lack of cheap material, and the consequent need to exchange it for another that multiplies the price, would lead to a higher percentage of the material in the total cost, surely placing it in first place ahead of labour. To avoid this type of drastic change, it is recommended to stockpile material when it is available at a good price and store it in order to prevent unaffordable losses of money for a small business. In that case, a certain storage space would have to be enabled or be available in which to store sufficient material to be able to respond to possible customer demands.

In summary, in order to reduce the cost of manufacturing pump parts by sand casting in Morocco, we suggest the following:

- To store raw material that is difficult to find and whose price fluctuates suddenly when its value is optimum.
- To reduce manpower by installing automated equipment.
- To organise production to save some energy by keeping the furnaces on during low-cost time slots and during the shortest possible time.

In this study, a very small order quantity of ten pumps was used, as the calculations were supposed to be based on a tailor-made product with small order size. However, if the number of pieces produced will be much higher than they would be in normal mass production processes (by the thousands) the image will be completely different. Taking into account a 5000-part order quantity, the allocations will change to be around 50% $C_{material}$, 1% C_{labour}, 5% C_{energy}, 30% $C_{tooling}$ and 15% $C_{overheads}$. The material and tooling cost will continue being the same as these do not depend on the production rate but are related to

the shape and size of the pump, whereas the cost of labour, energy and overheads will be divided by the amount to be produced, reducing their contribution drastically. From this calculation it is clear that the share of the drivers is highly dependent on the type of work demanded (tailor-made vs. mass production).

Comparing with some values found in the literature, Chougule and Ravi [11] allocated the following cost to the drivers studied for a 5000-part production requisition: 70% $C_{material}$, 5% C_{labour}, 10% C_{energy}, 1% $C_{tooling}$ and 10% $C_{overheads}$. These values are more comparable to those calculated for high production volumes obtained with the present tool. The main differences arise from the fact that the tooling cost calculated in that case was much smaller than the one calculated in the present work and that this value modifies the rest of the portions represented in Figure 7. In any case, it is obvious that the labour cost, which was the main driver when taking into account small tailor-made orders, is reduced drastically. The cost of the material then takes centre stage, placing it in first place above labour, machining and overheads.

In the present situation, in which market values of commodities such as energy or raw materials are climbing by the day, these allocations may vary quickly and gain importance for the overall cost.

These calculations can be used continuously, as an improvement tool to highlight drivers that are higher than expected and act on them to reduce internal costs.

4. Conclusions

The formulae and estimations shown in this paper were used to calculate the theoretical cost of manufacturing a radial pump by sand casting in Morocco. So far, the production of tailor-made products in the metallurgical industry in this country is limited to a few small companies and family-run businesses with small production loads. Therefore, know-how is limited, and many inputs used in the calculations were taken from the international ecosystem.

The studied pump is made up of various components, some of which have intricate shapes (for example, the impeller), so the design of the gating system bears a large part of the cost, especially if the production is small. This study has seen how easy it is to calculate the cost when the number of parts to be produced is much higher, since fixed costs such as design are diluted among more parts, lowering the impact on the final cost.

This tool can be used to perceive those fixed expenses that are difficult to reduce and upon which the foundry can intervene in order to minimize. Calculating the difference in cost obtained using different alternatives will help when making decisions regarding the automation of equipment, for how long one might be expected to amortize the equipment, the need to have material stored so as not to depend on market fluctuations, etc.

It is of utmost importance to highlight the need for precise inputs to obtain a useful tool. It is very challenging to give a real value of a product at an early stage since the changes that are included in the process will significantly vary its final cost. To obtain an accurate estimation of the cost of cast parts many details and information based on previous experience are needed, therefore, a close communication with the product designer and foundry is essential.

In this environment, the kind of tools that help provide an idea of the implications of changing materials, post-casting treatments, final surface finishing, etc. may allow a company to give faster and more accurate responses without compromising its profits, rendering the business more reliable.

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Nomenclature

MAD	Moroccan dirham
INR	Indian rupee
USD	United States Dollar
PCE	Product cost estimation
HT	Heat treatments
C_{total}	Total cost
$C_{material}$	Cost of the material
C_{direct}	Direct material cost
$C_{indirect}$	Indirect material cost
P_{metal}	Price of the metal used
W_{cast}	Weight of the cast part
f_m	Metal loss factor during melting
f_p	Metal loss factor during pouring
$C_{mould\ sand}$	Mould sand mixture cost
$C_{core\ sand}$	Core sand mixture cost
$C_{miscellaneous}$	Miscellaneous materials cost
$P_{mould\ sand}$	Price of mould sand mixture
$f_{recycle}$	Sand recycling factor
f_r	Casting rejection factor
$f_{mould\ rej}$	Mould rejection factor
$W_{mould\ sand}$	Weight of sand mould
$\rho_{mould\ sand}$	Mould sand density
$V_{mould\ sand}$	Total volume of the mould sand
V_{flask}	Volume of the flask
V_{cast}	Volume of the cast part
V_{gating}	Volume of the entire gating system
V_{feeder}	Volume of feeders
V_{core}	Volume of the core(s)
$P_{core\ sand}$	Price of core sand mixture
$W_{core\ sand}$	Weight of sand mould
$\rho_{core\ sand}$	Core sand density
$V_{core\ sand}$	Total volume of the core sand
$f_{core\ rej}$	Core rejection factor
C_{wood}	Wood cost for pattern
P_{wood}	Price of wood
V_{wood}	Volume of wood used to produce the pattern
C_{labour}	Cost of the labour
$C_{labour\ highly\ qualified}$	Highly qualified labour cost
$C_{labour\ technical}$	Technical labour cost
f_r	Factor for casting rejection
m	Number of designs
$f_{design\ rejection}$	Rejection factor for the design
$S_{high\ qualification}$	Salary per hour of the highly qualified worker
$l_{designHQ}$	Number of highly qualified workers involved in the design
t_{design}	Time spent in the design

n_{parts}	Number of parts produced from the design/activity
$f_{activity\ rejection}$	Rejection factor for activity i
n	Number of activities
$S_{technical}$	Salary per hour of the technician
$l_{activity}$	Number of technicians involved in certain activity
$t_{activity}$	Time spent in certain activity
C_{energy}	Cost of the energy
$C_{melting}$	Cost of the melting process
$C_{holding}$	Cost of holding the material at a certain temperature
$C_{heat\ treatments}$	Cost of the heat treatments
$C_{machining}$	Energy required for machining the metallic part
$C_{other\ energy}$	Cost of the other energy used for running the plant
P_{energy}	Price of the energy
$E_{melting}$	Energy required by the electric arc furnace for melting the metal
W_{metal}	Weight of metal needed
$t_{holding}$	Time that the holding process takes
$E_{holding}$	Energy required to keep the temperature of the melt constant during holding time
$C_{stress\ relieving}$	Cost of the stress relieving process
$E_{stress\ relieving}$	Energy required for stress relieving
$C_{annealing}$	Cost of the annealing process
$E_{annealing}$	Energy required for annealing
$C_{preheating\ and\ cooling}$	Cost of the preheating and cooling processes
$E_{preheating\ and\ cooling}$	Energy required for preheating and cooling
$C_{machining\ pp}$	Cost of the machining process per part
$E_{machining}$	Energy required to machine a part
$t_{machining}$	Time required to machine the part
$C_{tooling}$	Cost of the tooling
$C_{updates}$	Cost of software updates
$C_{consumables}$	Cost associated to consumables for the use of tooling
$C_{maintenance}$	Cost of the equipment maintenance
n_{up}	Number of updates
$P_{updates}$	Price of software updates
n_x	Amount of design, machined parts, etc. produced
$C_{overheads}$	Cost of the overheads
$C_{administration}$	Administration of the whole business
$C_{depreciation}$	Depreciation cost of the entire plant

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