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TECHNICAL PAPER

Proposal and evaluation of a selection procedure for cast parts

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Abstract The design of casting components is a complex activity, which is usually based on guidelines scattered in the literature, or based on the designer's accumulated experience. A single failure in the casting process selection can increase design and production time and, in critical cases, result in a collapse of the manufacturing and assembly of components. Nowadays the selection is made by prioritizing the features of the casting process, but this action could be carried out during the product development stage, assisting the designer. This could allow the project to adjust to a more viable casting process. In this context, our goal is to propose a selector for casting processes to be used during the early stages of the embodiment design. It was achieved through the use of quality function deployment and design for manufacturing (DFM) principles. Our proposal relates the component's main functions with each process characteristic (mass, minimum section thickness, draft angle, surface finish, dimensional tolerances, minimum lot and lead time) through a correlation matrix, resulting in importance indexes for these characteristics. Furthermore, the importance indices obtained are related to the capability of each casting process discussed, providing a process rating. A checklist based on DFM principles is also provided to guide the designer when a need for improvement is observed or no processes are suited for producing the desired part. For validation, two ferrous and two nonferrous cast parts were analyzed. The results were compared with other selectors described in the literature and with processes actually used in the industry. Thus, they have shown a good relation with the other methods, especially regarding the quantitative classification determined by the proposed selector.

Keywords Selector · Casting · Process

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1 Introduction

In Brazil, there are about 1400 small casting businesses, and the country is considered the seventh largest producer of castings in the world, producing about three million tons of molten materials per year, according to the Brazilian Foundry Association – ABIFA [1]. Revenue in 2012 was more than $13 billion. The great financial power of the area drives the research of new casting processes, as seen in the application of technologies such as stereolithography, selective laser sintering, and fused deposition modeling [2]. This development is leveraged by the large existing market competition and the increasing demand for quality by consumers.

The choice of the casting process is essential to the degree of dimensional accuracy as well as to the definition of the finish and mechanical properties of the component to be manufactured [3]. Despite the existence of many methods for making molten items, the tendency of professionals in designing these items is to use materials and processes that they have familiarity with, which is still a prevalent tradition. This action results in the removal of processes and combinations of materials that could be more economical [4]. Thus, the selection of manufacturing processes plays an important role, as the choice of the most appropriate process for the characteristics of the component results in advantages, such as cost and time savings and increased reliability due to the reduction of the probability of production component failure. On the other hand, a mistaken choice, besides the significant increase in design and manufacturing time, contributes to potential manufacturing and assembly failures that result in high costs.

Ashby [5] and Magrab [6] observe that the choice of a casting process generally takes into account the process characteristics, such as production capacity and facilities. Some selectors also consider importance weights related to the component features in their casting process. Mainly, these features are: material, mass, minimum section thickness, dimensional tolerance, and annual manufacturing lot minimum [7, 8]. Swift and Booker [9] also compare the final characteristics of the designed castings with the selected process. However, these selectors disregard the function and final application of the product to be cast. In this context, our work focuses on the development of a selector of casting processes that uses this information during the product development stage, optimizing the project.

First of all, a review of the related literature was necessary in order to obtain parameters for the foundation and development of the casting process selector. Moreover, the development of the conceptual structure of the selector is based on the characteristics of the casting process and selection criteria. The construction of a main checklist along with specific checklists by DFM was done in parallel. The set of conceptual models of selection associated with checklists gives the desired selector, whose application is industrially produced with nodular cast iron, brass alloy and copper alloy. Finally, the analysis of the results of the objects studied reinforces the selector validation.

2 Literature review

According to Ashby [5], the first step of the development of a new component is the specification of its function in the product. Functions related to consumer needs and product functioning have a higher value in the market and should be preferred, while an attempt is made to reduce the number of parts that have secondary functions in the product. Based on the function, the requirements of form and material for the part are defined. Besides being related to each other, these requirements also determine the universe of options for manufacturing processes. This correlation between function, shape, material and process is essential to the understanding of the selection methods of the manufacturing processes.

Ashby [5] and Magrab [6] proposed the selection of processes using a comparative matrix between the component and capacity requirements of the production process. The selection made by these authors is wide, as it covers the joining processes, shape and surface finish and heat treatment; and for specifying the processes, it only considers the most common ones (green sand, die casting, precision and permanent mold casting, low pressure). In the literature, it is possible to find several forms of selection processes, among which we can mention: expert systems, process information maps, rational methods, set of rules, multi-criteria method and QFD [7–12].

Selecting from an expert system [7, 8] is to identify the alternatives that are relevant and rank them according to their performance or the conversion of a knowledge base (if–then rules).

The selection process from process information maps (PRIMAs) provides a path for the technological and economic details of each process, where the main feature is the inclusion of process capability. The capability is related to the contents of processes as Cpk (process capability index) and the choice is made from six steps, namely: (1) obtaining the necessary annual production; (2) choice of material that meets the necessary conditions; (3) choosing the processes to be utilized in PRIMA; (4) formulation of PRIMA; (5) consideration of market positioning of the process and obtaining the estimated cost of the alternatives; (6) treating the selected process and comparison with component requirements [9].

In the rational method, the selection procedure evaluates the processes according to their properties and characteristics, classifying them in the database from the weight of each criteria. The selection procedure is based on the principle that the component characteristics restrict the use of certain manufacturing processes. Darwish and Al Tamimi Habdan [10] use this method to select the type of welding processes.

Karthik et al. [11] select processes through software, by assigning weights (0 to 5) to the selection criteria according to a set of rules. The characteristics that have values outside the range established by the selector are assigned the minimum score, and values corresponding to the ideal intervals for each process receive the maximum score. Values that fluctuate between the expected minimum and the optimal range are evaluated as linear equations.

The multi-criteria selection method for casting processes (MSMCP), proposed by Setti [12], consists of (1) technical selection modules which are designed to anticipate the selection activities of processes in the preliminary design phase, and (2) the economic selection module, in order to anticipate the selection process activities necessary for the detailed design phase. The MSMCP considers foundry processes for the manufacture of near net shape or net shape parts. However, it does not include material selection. Setti [12] proposes innovation not addressed by methods available in the literature, including: the consolidation of several information sources of processes to be employed by MSMCP via an aggregation function; use of environmental features as foundry process selection criteria; and use of manufacturing cost estimates to develop a selection strategy based on economic evaluation.

All selectors mentioned above make the selection of the casting process from the comparison of the component characteristics versus the process capabilities. Only Swift and Booker (2003) consider the component requirements at the end of the selection in order to compare with the obtained requirements. Darwish and Al Tamimi [7] and Setti [12] assign weights for each production process, in order to set values for the characteristics considered most important.

Another approach was taken by Chakraborty and Dey [13], which used QFD principles to build the comparison matrix. In this matrix, the comparison is made using numbers or symbols representing the relation strength (importance) among properties. The material characteristics and applicable shapes are considered critical shape factors, and when the process does not meet the requirement, it is then excluded from evaluation. On the other hand, for the procedures approved by the critical features, there is an individual assessment which provides an index that represents the process in a particular application. The process with the highest index is considered the most appropriate. The authors successfully used this method as a way to select non-traditional machining processes, although they do not bring new elements to the comparisons between the materials or process characteristics.

Therefore, the Chakraborty and Dey [13] method brings a new approach. They report the same requirements addressed by Swift and Booker [9], Darwish and El-Tamimi [7], Karthik et al. [11] and Setti [12]. The manufacturing process selection methods available do not take into account the component of the main functions to be manufactured at the beginning of the selection, but only the capabilities of casting processes and their relation to the suitability of the project.

3 Development of the casting process selector using QFD and DFM

3.1 Methodology

The hypothesis that drove our research was that a procedure inspired by QFD principles for the selection of casting processes is possible and provides a simpler way to perform the decision of which casting process is more suited to a specific part. It is justified since, in our experience, we observed that designers are more comfortable performing the first level of decision (to adopt a casting process or not) than the second level (which casting process is best suited) since it is well-established in the literature. The decision of the casting process will impact directly on the geometry of the part and, consequently, on the geometry of adjacent parts.

To develop the proposed selection procedure, the following steps were adopted:

- Development of the process selector structure: it was divided into three tasks. First, we created the conceptual model based on QFD principles. Second, we defined the selection criteria, based on a literature review. Third, we gathered values for the defined criteria.
- Checklist development: A checklist was also developed to complement the proposed selector. To do so, the available DFM literature regarding casting processes was used. It was organized according to the studied processes in order to facilitate its use by the designer. So, if the results of the selector indicate weak specifications, or no process is selected, the designer could use a quick reference to correct the initial design.
- Proposal Evaluation: to consider something as valid, it has to achieve results that are reproducible and rigorous. In order to achieve this goal, we considered four real parts produced by distinct metal-mechanic industries. The validation is performed based on the results from the proposed selector compared to the results from other selectors and with the processes currently adopted by these industries.

3.2 Development of the process selector

In this paper, a conceptual model based on QFD principles is proposed for the selection of casting manufacturing processes. QFD is an approach developed by Akao [14] for product design based on the deployment of information regarding customer requirements into engineering information. Cheng and Melo Filho [15] affirm that the use of the QFD method originally had two specific purposes: (1) assisting in the new product development process, searching for, translating and transmitting the customer's needs and desires; and (2) ensuring quality. One of the most popular elements of QFD is the House of Quality. Chakraborty and Dey [13] state that a prerequisite for the implementation of QFD is benchmarking, which allows us to understand what the consumer wants, the importance magnitude of the product features, as well as the expected performance of different product characteristics. This is considered to be a management tool to model the dynamic of the development process. The QFD characteristic easily makes comparisons between different attributes and criteria and assists in the analysis of the influence of the criteria [13].

QFD is a more comprehensive process than only the House of Quality and involves its deployment in other motives following a given conceptual model. This model can be presented as a set of tables and matrices of a given development project. A complete conceptual model includes four phases: positive quality (or simply unfolding quality), technology, cost and reliability (or negative quality). However, the decision of going on with these four dimensions depends on the objectives of each development project. Therefore, it can be said that the type of conceptual model to be built is entirely dependent on the objectives of the project, the style of company and the nature of the product [15].

Our proposal of a casting process selector is meant to be used during the early stages of the embodiment design. At this point, much of the product architecture is already defined, and some parts are selected as candidates for the casting process. In addition, the function and some design parameters (geometry, finishing, materials, etc.) of these parts are also known, so the minimal information needed to perform the casting process selection is available. The conceptual model used, shown in Fig. 1, consists of two parts: (a) a correlation matrix and (b) a selection matrix. In order to evaluate the proposed method and convenience for design, the matrices were built in an electronic spreadsheet.

The correlation matrix correlates component functions and features with the casting process characteristics and thereby obtains the importance of the characteristic processes (mass, minimum section thickness, draft angle, surface finish, dimensional tolerances, minimum lot and lead time). In the correlation matrix core, the correlation (intersection between rows and columns) must be evaluated in order to comply with a scale ranging from 0 to 5, where 0 means null correlation (inexistence of correlation) and 5 means very strong correlation.

The characteristics of the casting process to be used on the selector were chosen from the literature available on the selectors as shown in Table 1. At this stage, if it is not already available, it is necessary to provide the design goals for each process characteristic. Because component size can influence the value of dimensional tolerance, the dimension related to the dimensional tolerance must be provided for this feature.

To distinguish between ferrous and nonferrous materials, it was necessary to build two selection matrices, one for each group of processes, because some of the casting processes are not applicable in both cases. For each process characteristic, four levels for the "value of the characteristics" were established, as shown in Table 2, namely: (1) extreme minimum, (2) minimum, (3) maximum and (4) extreme maximum. Notice that, in this case, there is no data for the surface finish extreme maximum, so a large value was adopted to represent infinity. These particular values were determined from the comparison of the values suggested by Metalcasting Design and Purchasing [16], Swift and Booker [9], ASM Handbook [17] and Bralla [18].

All values of the characteristics are organized according to the casting process in the selection matrix. To obtain the prioritization rank, the design goals are

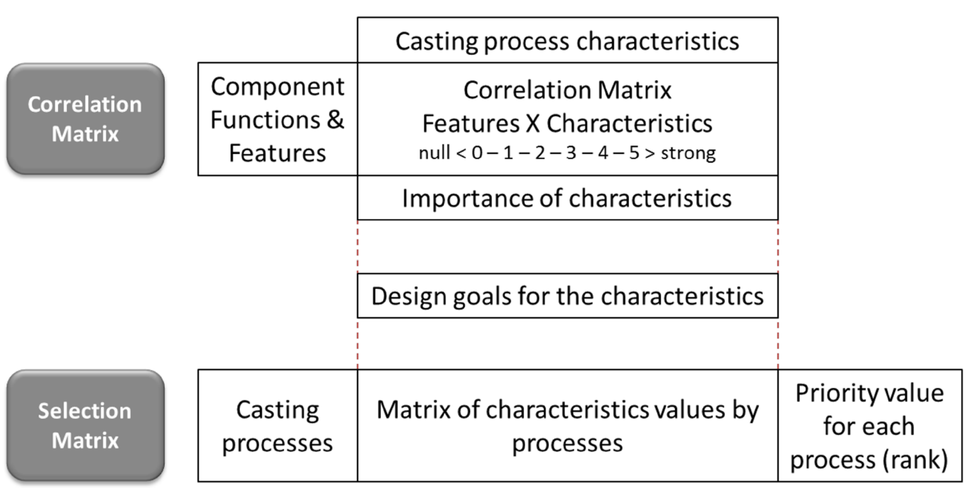

Fig. 1 Conceptual model for the selection of casting processes

Table 1 Adopted selection criteria and authors of the casting process selectors

Selection Criteria (features)	Darwish and El-Tamimi [7]	Er and Dias [8]	Swift and Booker [9]	Karthik et al. [11]	Setti [12]
Material	X	X	X	X	X
Mass (kg)	X	X	X	X	X
Minimum section thickness (mm)	X	X	X	X	X
Draft angle (°)			X	X	X
Surface finish (Ra)	X		X	X	X
Dimensional tolerances (mm)	X	X	X	X	X
Minimum lot (components per year)	X	X	X	X	X
Lead time (days)				X	X

Table 2 Surface finish (Ra) in the permanent mold (gravity) process

References	Extreme minimum	Minimum	Maximum	Extreme maximum
Metalcasting design and purchasing [16]	4.12	5.72	9.61	–
Swift and Booker [9]	0.8	0.8	2.3	–
ASM Handbook [17]	2.5	3	7.5	–
Bralla [18]	–	3.8	13	–
Adopted	0.8	2.05	9.61	450,000

compared with the values of the characteristics of each casting process. For ferrous metals, they are: manual green sand, automated green sand, cold box resins, shell molding resins, ceramic molding, precision casting (investment casting), centrifugal casting mold with sand and permanent mold casting with gravity. From this comparison, indicators of process capability are determined, with possible values of 0, 1, and 2, matching the range in which the component characteristic is found, where:

- 2: design goal is between the minimum and maximum value (within the usual limits);
- 1: design goal is between the minimum and extreme minimum, or between the maximum and extreme maximum (within the extreme limits);
- 0: design goal is above the extreme maximum or below the extreme minimum (out of process limits).

The "priority value for each characteristic" is then obtained by multiplying the corresponding value of process capability (0, 1 or 2) with the "importance of the characteristic" obtained from the correlation matrix. Therefore, the "priority value for each process" is the result obtained by the sum of all the "priority values of the characteristics" for each casting process (rows in the selection matrix). This value is then normalized by dividing it by the highest "priority value for each process" and multiplied by 10, resulting in a range from 0 to 10, thus facilitating the interpretation of the final result. If any process obtains an index of 0 in any feature, its final score will be 0; in other words, the process is unable to produce the desired component characteristics.

The same selection process described above can be used for nonferrous materials only by including the following casting processes in the selection matrix: low pressure die casting, squeeze casting and centrifugal casting with permanent mold (replacing sand mold).

3.3 Checklist development

In our opinion, to provide only a process selector without also providing an instrument to correct the undesired results and guide design improvement is to provide an incomplete tool. Undesired results include a large number of design goals including extreme limits of process characteristics and the absence of processes capable of achieving the desired design goals. To help designers to review their design goals, we developed a checklist based on design for manufacturing (DFM) principles to evaluate the outputs from the proposed process selector.

DFM incorporates information related to manufacturing, helping communication between all elements and enabling project adaptations during each stage of product manufacture [4]. Furthermore, Bralla [18] defines DFM as "a technique based on knowledge that evokes a series of guidelines, principles, recommendations or rules for a product design in order to facilitate its manufacture."

Our DFM checklist was based on the recommendations found in the design literature for cast products, integrated into the selector, so it assists the designer with corrections of part design parameters after the final process ranking is generated by the selector. The integration of these two tools can be better observed in the flowchart illustrated in Fig. 2. The process begins with the geometric features and other project requirements for the part. This information is included in the proposed process selector, which provides the (normalized) process ranking. If the selection process provides good results, we suggest applying the Main Checklist (Table 3) followed by the Specific Checklist for each process. If a checklist item is not in agreement, the user must evaluate the changes taking into account the costs and physical and dimensional limits. After part redesign, once again the checklist should be applied to the next ranked process.

A checklist was created (Table 3) including five specific casting processes: green sand and shell molding, precision casting, plaster mold, permanent mold gravity and permanent mold under pressure. The proposed checklist also includes general casting information.

4 Selector application and evaluation

For process selector evaluation, real parts applied in the local metalworking industry were used. The parts obtained vary in function and materials, as shown in Table 4.

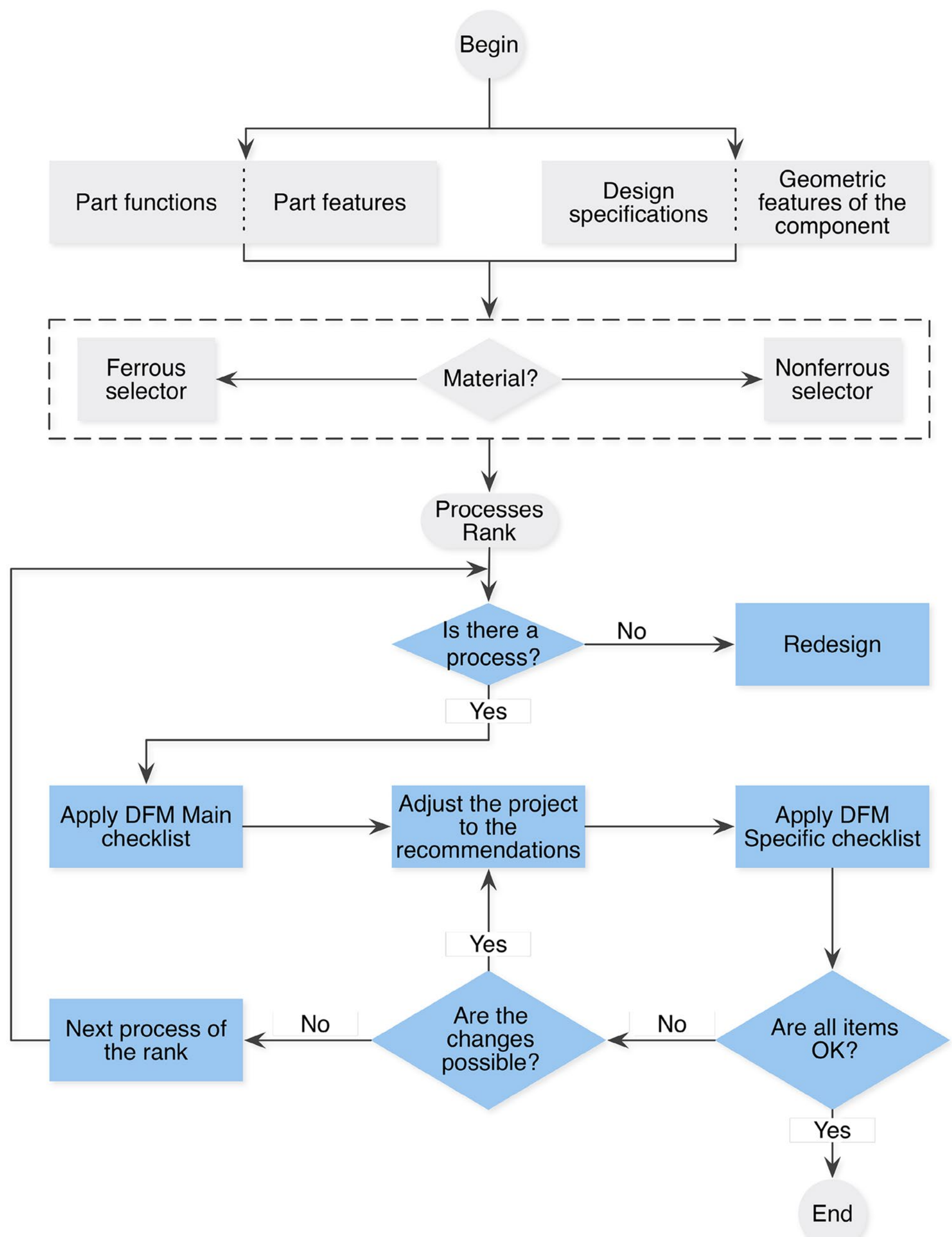

Fig. 2 Selector operation flowchart integrating DFM

Table 3 Checklist for casting processes

Process	Verification	Ok?
Casting (general)	Are abrupt approach/departure angles and small radius joints avoided?	
	Are the section thicknesses as uniform as possible?	
	Are the changes in section thickness as soft as possible?	
	References: [1, 18, 19]	
Green sand and shell molding	Do the section changes follow the literature recommendations?	
	Do the T-joints have a member with the lowest possible thickness?	
	Do the L- joints follow the literature recommendations?	
	Do the V-joints follow the literature recommendations?	
	Do the shoulders follow the literature recommendations?	
	Have all possible X-shaped sections been eliminated?	
	Were the gates correctly sized?	
	Are the holes larger than 6 mm in diameter for green sand or larger than 3 mm for shell molding?	
	Is the machining allowance between 1.5 and 6 mm?	
	Is the parting line a continuous line around the part?	
	References: [9, 18]	
Precision casting	Is the fillet radius minimum greater than 0.75 mm? (preferably between 1.5 and 3.0 mm)	
	Do the holes have diameters larger than 1.5 mm for ferrous and 2.2 mm for non-ferrous?	
	Is the ratio between depth and diameter 4:1 for ferrous and 5:1 for non-ferrous?	
	Inserts are not possible. Do projects not need them?	
	References: [9, 18]	
Plaster mold casting	Are the dimensions suited to process requirements?	
	Is the machining allowance around 0.8 mm?	
	Are holes larger than 13 mm avoided?	
	Is the material not magnesium?	
	References: [9, 18]	
Permanent mold gravity casting	Are the holes in the direction of separation of the mold?	
	Are the dimensions of the internal radius larger than the mean thickness of the section?	
	Are the dimensions of the external radius larger than 3 times the mean thickness of the section?	
	Is the variation in the transverse section gradual?	
	Is the allowance for machining between 0.8 and 2 mm?	
	Are the holes larger than 5 mm?	
	Are the critical dimensions not through the parting line?	
	References: [9, 18]	
Permanent mold under pressure casting	Is the added material to be removed in machining between 0.25 and 0.5 mm?	
	Do the diameters of the holes respect the recommendations?	
	Are the section changes as soft as possible?	
	Do section changes respect the literature recommendations?	
	Are the holes perpendicular to the parting line?	
	Are the holes larger than 0.8 mm in diameter?	
	Are the critical dimensions not through the parting line?	
	References: [9, 18, 20]	

4.1 Applying the selector onto the industrial parts

As an example, we selected the bogie (Table 4a), which is cast with nodular cast iron. This part is used on the backside of trucks as support for the torsion bars and spring rocker, and it has motion coupled with the displacement of the suspension. Thus, after casting, this part (1) is painted, (2) provides support for other parts and performs the work in motion, and (3) is mounted to a vehicle. From this information, we can determine the importance of the characteristics of the processes as shown in Table 5. As occurs with other QFD-like procedures, these values may vary

Table 4 The metal-mechanic industry parts analyzed

Part	a Bogie	b Front wheel hub	c Household faucet body	d Industrial plug
				
Material	Nodular cast iron	Nodular cast iron	Brass alloy	Copper alloy
Mass (Kg)	52	24.5	0.367	0.66
Minimum section thickness (mm)	9.5	10	3.25	3.5
Draft angle (º)	2	1	NI[a]	3
Surface finish (Ra)	2	2.5	2.71	4
Dimensional tolerances (mm)	±0.8	±0.8	±0.5	±0.5
Minimum lot (components per year)	50	200	80,000	NI
Lead time (days)	Not specified	Not specified	Not specified	Not specified

according to the analysis of the design team. Table 5 was completed according to our research team's experience. The same procedure was performed for the other parts of Table 4, and the final results are also presented in Table 5.

After obtaining the importance values of the characteristics, the priority value for each process is calculated for each part. For instance, the results for the sand casting process with cold box resins for the bogie are shown in Table 6, along with the respective importance values of the characteristics obtained in the correlation matrix (Table 5) shown in Table 6 (column C). The values for the bogie in column B are compared with the characteristic values of the cold cure process (columns D to G) in order to find the associated indicators (column H). Thus, the importance values (column C) are multiplied by the correlated indicators (column H) giving the priority value of the characteristic (column I). The value 73, obtained by the sum of values from column I, corresponds to the non-normalized priority index for this process. It was the greatest value obtained among the listed ferrous casting processes and, after normalized, it received a score of 10.00.

After filling in the data required by the process selector, the results are presented as a ranking, as shown in Table 7. As a result, for the selector of the bogie, it appears that the

Table 5 Correlation matrix for the importance values of each characteristic of the parts

	Characteristics of the component Bogie						
	Mass (kg)	Minimum section thickness (mm)	Draft angle (º)	Surface finish (Ra)	Dimensional tolerances (mm)	Minimum lot (components per year)	Lead Time (days)
Functions							
Support springs and torsion bar (mounted)	3	0	3	0	3	0	0
Working in movement	5	2	0	0	2	0	0
Applications							
Auto industry part	5	5	0	0	5	5	5
Painting	0	0	0	4	0	0	0
Σ (Importance of the characteristics)—Bogie	13	7	3	4	10	5	5
Σ Front wheel hub	12	11	3	7	11	3	5
Σ Household faucet body	6	3	3	4	5	11	3
Σ Industrial plug	1	1	5	3	3	1	1

process of sand-curing cold resin was the most appropriate (10.00) followed by precision casting (9.86) and ceramic mold process (9.18). All the other processes were considered unable to fabricate the part with the desired characteristics (0.00). It is worth noting the small difference between the scores for each case, demonstrating the fulfillment of requirements for the three casting processes. Thus, the final choice among the possible options is a decision that depends on the designer. It is recommended to consider the company's expertise or to perform a detailed survey for suitable candidates to provide the desired part with the desired process.

Table 7 also shows that the most suitable processes for the front wheel hub are automated green sand and resin sand with cold curing, permanent mold at low pressure for the household faucet body, and sand with resin (cold curing) for the plug.

To perform the validation of the results, Table 8 was constructed, which shows a comparison between the results of the proposed selector with the literature [8, 11] and with the actual process used in industry. For the ferrous parts, strong matching among the results is observed. However, it is not possible to reach the same conclusion for the nonferrous parts, where a great discrepancy among all selectors was observed. Though, if the second candidates presented by the proposed selector are also considered, it is possible to notice that our proposal matches well with the actual processes in both parts. It is important to highlight that Er and Dias [11] did not determine a process for the plug casting because their selector excludes cases in which the part characteristics are placed beyond the ordinary minimum or ordinary maximum value.

4.2 Application of DFM—checklist for permanent mold gravity casting in the household faucet body

To illustrate the use of the DFM checklist and its correlation with the casting process selector, it was applied to the household faucet body part. It was chosen since its result showed great divergence in Table 8. Taking into account that this part is presently manufactured through the permanent mold casting process, it was decided to improve the current design based on the DFM guidelines for this process (Table 3). The checklist results (Table 9) pointed out three non-conformities in the part design, for which improvement suggestions were provided.

4.3 Tool final evaluation

When evaluating the proposed procedure against its usability, it is possible to see that it incorporates all benefits of a well-known structure such as the one provided by QFD. It includes the ability to deal with a large amount of information, correlating data and providing importance grades. It is important to notice that our proposal already includes all technical information regarding the casting process. It is only necessary to include design information. So, our proposal could be considered faster than a traditional QFD.

Table 6 Summary of the characteristic values and their importance for the sand casting process with cold box resins for the bogie part

A	B	C	Characteristic values of the cold cure process				H	I
			D	E	F	G		
Features of the part	Design goal for [A]	Importance [A]	Extreme minimum	Ordinary minimum	Ordinary maximum	Extreme maximum	Associated indicator	Priority value of the characteristic (column C × column H)
Mass (kg)	52	13	0.09	0.23	68.04	45,000	2	26
Minimum section thickness (mm)	9.5	7	3	4.76	NE	NE	2	14
Re-entrant angle (°)	2	3	NE	1	2	NE	1	3
Surface roughness (Ra)	2	4	0.91	3.43	13.73	NE	1	4
Dimensional tolerances (mm)	±0.8	10	0.41	0.66	NE	NE	2	20
Minimum lot (components per year)	50	5	1	1	NE	NE	1	5
Lead Time (days)	NS	5	15	45	NE	NE	1	1
Priority value for the process (not normalized)								73

NS not specified, *NE* non-existent

Table 7 Final ranking of priority value of processes (normalized) for the evaluated parts

		Mass	Minimum section thickness	Re-entrant angle	Surface roughness	Dimensional tolerances	Minimum lot	Lead time	Score	Normalized Score
Bogie	Green sand—manual	18	22	3	0	0	6	1	0	0.00
	Green sand—automated	18	22	3	0	0	6	1	0	0.00
	Cold box	18	22	3	5	18	6	1	73	10.00
	Shell molding	9	22	3	10	9	0	1	0	0.00
	Ceramic mold	9	22	6	10	18	3	1	69	9.45
	Investment casting	9	22	6	10	18	3	1	69	9.45
	Lost foam	9	22	6	5	18	0	1	0	0.00
	Centrifugal casting	18	22	6	0	0	3	1	0	0.00
	Permanent mold—low pressure	9	22	3	0	18	0	1	0	0.00
Front Wheel Hub	Green sand—manual	16	18	0	7	0	6	1	0	0.00
	Green sand—automated	16	18	3	7	0	6	1	0	0.00
	Cold box	16	18	3	7	22	6	1	73	10.00
	Shell molding	8	18	3	14	11	0	1	0	0.00
	Ceramic mold	8	18	3	14	22	3	1	69	9.45
	Investment casting	8	18	3	14	22	3	1	69	9.45
	Lost foam	16	18	3	7	22	0	1	0	0.00
	Centrifugal casting	16	18	3	7	0	3	1	0	0.00
	Permanent mold—low pressure	16	18	3	7	22	0	1	0	0.00
Household faucet body	Green sand—manual	6	3	1	4	0	0	1	0	0.00
	Grenn sand—automated	6	3	1	4	0	11	1	0	0.00
	Cold box	12	6	1	4	10	11	1	45	8.03
	Shell molding	12	6	1	8	0	22	1	0	0.00
	Ceramic mold	6	6	1	8	0	22	1	0	0.00
	Investment casting	12	6	1	8	10	11	1	49	8.75
	Lost foam	6	6	1	4	5	11	1	34	6.07
	Centrifugal casting	0	6	1	4	0	11	1	0	0.00
	Permanent mold—gravity	12	6	1	4	5	22	1	51	9.11
	Plaster molding	12	6	1	8	10	11	1	49	8.75
	Permanent mold—low pressure	12	6	1	4	10	22	1	56	10.00
	Die casting	12	6	1	8	0	11	1	0	0.00
	Squeeze casting	12	0	1	8	10	22	1	0	0.00

Table 7 continued

		Mass	Minimum section thickness	Re-entrant angle	Surface roughness	Dimensional tolerances	Minimum lot	Lead time	Score	Normalized Score
Plug	Green sand—manual	2	1	5	3	0	1	1	0	0.00
	Grenn sand—automated	2	1	10	3	0	1	1	0	0.00
	Cold box	2	1	10	6	6	1	1	27	10.00
	Shell molding	2	1	10	0	0	1	1	0	0.00
	Ceramic mold	2	2	10	6	0	1	1	0	0.00
	Investment casting	2	2	10	0	6	1	1	0	0.00
	Lost foam	2	1	10	6	3	1	1	24	8.89
	Centrifugal casting	0	2	10	3	0	1	1	0	0.00
	Permanent mold—gravity	2	2	5	3	3	1	1	17	6.30
	Plaster molding	2	2	5	0	6	1	1	0	0.00
	Permanent mold—low pressure	2	2	5	3	6	1	1	20	7.40
	Die casting	2	2	5	6	0	1	1	0	0.00
	Squeeze casting	2	0	5	0	6	1	1	0	0.00

Considering generality, our proposal takes into account all typical casting processes and their customary technical features as considered by the specialized literature and casting expert organizations. So, it is possible to assume that it is broadly applicable, leaving out only special and state-of-the-art castings.

Evaluating the proposal efficiency, considering the comparison of processes and parts presented in this paper, we observed that our results corresponded well with the industrial practice, demonstrating the high efficiency of the method. The same could be said about the comparison with other casting process selector when considering ferrous materials. However, when considering non-ferrous materials, no convergence was observed. Further research can be performed to better understand this divergence.

It is also possible to compare our proposal efficiency with other technical procedures, such as the Analytical Hierarchy Process (AHP). According to Vaidya and Kumar [21], AHP is one of the most used multi-criteria methods. The definition of the priority vector from paired comparison matrices is the core of AHP method. This method can be used as an auxiliary tool for process selection as performed by Akarte et al. [22] and Nagahanumaiah et al. [23]. In the work of Akarte et al. [22], the AHP method was used to assign weight to the nineteen criteria used in the casting process selection process. Nagahanumaiah et al. [23] studied the selection of rapid prototyping processes for tooling. The method was used to determine the relative importance of the tooling requirements requested by the customer.

In the case of the present selector, the importance of each component characteristic (mass, minimum section thickness, draft angle, surface finish, dimensional tolerances, minimum lot and lead time) was obtained by the matrix correlation between the function of the component and the weight given by the designer, effectively simplifying this part of the process when compared with the AHP features.

5 Conclusion

The proposed method for the selection of the casting process based on QFD principles proved to be valid. The results achieved align well with those obtained by well-known selectors and by the processes adopted by industry, especially for ferrous materials. The use of QFD principles led to a solution that easily converts design information (functions, features, geometries and materials) into a ranked list of suitable processes, facilitating the analysis and interpretation of results. Additional research could be done to address the differences among results obtained for non-ferrous materials in order to identify the root of the discrepancies.

Table 8 Comparison between the selection processes

	Bogie				Front wheel hub				Household faucet body				Plug			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Green sand—manual																
Green sand—automated					X											
Cold box	X	X	X	X	X	X	X	X					X			X
Shell molding																
Ceramic mold																
Investment casting	O				O					X						
Lost foam													O			
Centrifugal casting																
Permanent mold—gravity									O			X				
Plaster molding										X	X					
Permanent mold—low pressure									X						X	
Die casting										X	X					
Squeeze casting																

1 Proposed selector, *2* Er and Dias [8], *3* Karthik et al. [11], *4* industry/part provider, *X* first choice, *O* second choice

Table 9 Main checklist, household faucet body

Process	Verification	Ok?
Casting (general)	Are abrupt approach/departure angles and small radius joints avoided?	NO
	Suggestion: 0.5 mm junction radii joints should be raised to 3 mm	
	Are the section thicknesses as uniform as possible?	Yes
	Are the changes in section thickness as soft as possible?	Yes
Permanent mold	Are the holes in the direction of separation of the mold?	Yes
	Are the dimensions of the internal radii larger than the mean thickness of the section?	Yes
	Are the dimensions of the external radii larger than three times the average thickness of the section?	NO
	Suggestion: increase external radii to 3.5 mm in the project	
	Is the variation in transverse section gradual?	Yes
	Is the allowance for machining between 0.8 and 2 mm?	Yes
	Are the holes larger than 5 mm?	Yes
	Are the critical dimensions not located on the parting line?	NO
	Suggestion: move the dimensions of 8 mm × 3 mm × 2.5 mm out of the parting line	

To complete the selection process, a process checklist based on DFM guidelines is also provided, allowing designers to perfect the design of a part for a chosen process or to correct its design when the selection process is unsuccessful (i.e., there is no process capable of producing the desired part).

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