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Sustainability-Based Evaluation of Casting Gating Systems: a Multi-Criteria Decision-Making Approach

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Abstract

The selection of the most appropriate casting gating system design is one of the most critical decision-making tasks in foundries as it is closely associated to the amount of air inclusions and surface defect concentration, which should be minimal in the final casting product to ensure superior quality and enhanced mechanical properties. Moreover, the design of the gating system influences the material and energy usage and consequently the cost of the sand casting manufacturing process. Therefore, its design should be thoughtfully considered and planned. In this investigation, Multi-Criteria Decision-Making (MCDM) is being coupled with Computational Fluid Dynamics (CFD) simulations in order to select the optimal gating system design with respect to the sustainability of the process. Besides process energy, three additional criteria were used for the evaluation of the gating system performance, namely: air entrainment, surface defect concentration and mould cost. CFD simulations were performed to evaluate each one of the 6 gating system designs considered against each one the aforementioned criteria. The selection of the most appropriate gating system was performed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

Keywords: Multi-Criteria Decision-Making (MCDM); TOPSIS; Computational Fluid Dynamics (CFD); Sand Casting; Gating System Design

1. Introduction

Sand casting is one of the oldest and most widely used casting processes. During this process, alloys are heated up to a temperature slightly higher than their melting point and subsequently poured into the cavity of a sand mould;

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during the solidification process, the liquid metal obtains the desired shape and eventually, the final cast component is removed from the mould. Traditionally sand casting has been used for low-volume production; however, the increased automation introduced into the process allowed for increasingly faster fabrication of sand moulds and consequently high-volume production rates [1].

There are two main physical processes involved in sand casting, namely: (a) mould filling and (b) solidification. Nowadays, the evolution of the computing power as well as the numerical modelling techniques has rendered the numerical investigation of casting processes feasible. In this context, CFD has found a lot of applications across a wide variety of casting processes ranging from traditional sand casting [2] to more contemporary methods, such as Low Pressure Die Casting (LPDC) [3] and the Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) technique [4]. Moreover, computational models being capable of predicting the formation of defects such as oxide films, air entrainment and porosity have been integrated to the existing casting modelling software, as reported by Reilly et al. [5].

The aforementioned models were used later on as a stepping stone for the numerical optimisation of casting systems. Sun et al. [6] employed the Taguchi method [7] and performed multi-objective optimisation using four gating system parameters (ingate height/width, runner height/width) in order to simultaneously optimise the filling velocity, shrinkage porosity and product yield. Lee et al. [8] focused on the High Pressure Die Casting Process (HPDC) and compared 4 different mold runner designs in order to identify the one leading to minimum porosity. Their results were verified against experimental data. HPDC was also investigated by Krimpenis et al. [9], who identified the optimum HPDC parameters in order to minimise defect concentration. They also used the Taguchi method to establish a relationship between the defect concentration and the process parameters; subsequently, they fed their simulation data to an Artificial Neural Network (ANN) which was successfully trained to predict defect concentration and solidification time. Finally, the authors implemented Genetic Algorithms (GAs) in order to evaluate the optimal set of the HPDC parameters leading to superior final product quality. In another investigation, Papanikolaou et al. [10] developed a multi-objective optimisation framework in order to identify the optimal values for the width and height of the feeders used in the CRIMSON process. Their CFD model was verified against x-ray computer tomography images while the optimisation objective was the simultaneous minimisation of shrinkage porosity of the final cast product and the maximisation of the yield.

Although optimisation frameworks can facilitate the estimation of the optimal process or design parameters, most of the times, a large number of computationally expensive simulation runs are required to obtain the optimal set of solutions. In the case where a discrete number of alternatives/solutions is given, Multi-criteria Decision-Making (MCDM) techniques should be favoured. MCDM models have been extensively applied in the context of manufacturing systems. Some examples of their implementation include the selection of the optimal Flexible Manufacturing Systems (FMSs) configuration [11] and appropriate robots [12] as well as for the evaluation of manufacturing plants' performance [13].

In this study the TOPSIS method has been implemented to identify the most sustainable gating system design among a set of 6 alternatives. Four criteria, strongly related to the quality of the final cast product (air entrainment and surface defect concentration) and falling under the *environmental sustainability* and *economic prosperity* goals the Triple Bottom Line (TBL) approach [14] (process energy and mould cost), were used for the assessment of the available designs. The first 3 criteria of the current analysis have been evaluated using CFD simulations of the mould filling process while the mould cost has been taken by online sources.

2. Methodology

2.1. CFD model

In this study 3 trivial design concepts of the gating system were investigated as illustrated in Figure 1. The selection of these concepts was based on the fact that the geometry of the gating system affects the developed flow field and consequently the quality and of the final product and the process energy. For each of one of these concepts, a circular and a square cross section were considered; thus 6 cases were examined in total. In order to enable comparison between the circular and square cases, by maintaining the filling rate constant, the surface area of the duct was set to be equal between the two cases. More specifically, the diameter of the circular cross section was set to 20 mm and the edge length of the square was set equal to 17.7245 mm according to:

$$h = \sqrt{\pi \left(\frac{D}{2} \right)^2} \tag{1}$$

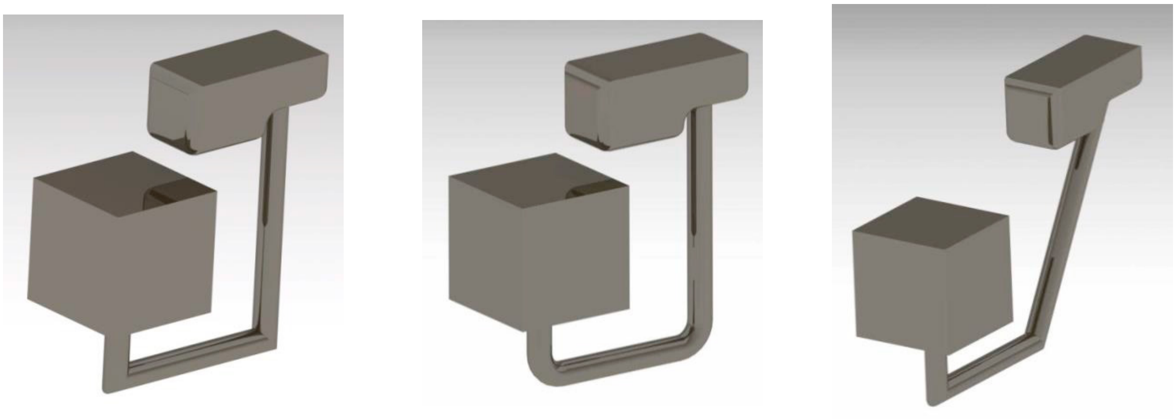
(a) (b) (c)

Figure 1: (a) Basic gating system design, (b) Gating system with fillets and (c) Inclined sprue

The liquid metal was considered to be LM25 Aluminium alloy while a metal source was placed on top of the stepped pouring cap as shown in Figure 2. The velocity normal to the mass source was 0.1 m/s while the mass flow rate was equal to 0.17 kg/s. In order to control the filling process 3 probes were used (Figure 2). When the liquid metal reached the level of Probe 3 (z-coordinate), the metal source was removed. Moreover, the CFD simulation was terminated if and only if both of the following two conditions were fulfilled:

1. The liquid fraction at the level of Probe 2 was greater than 0.99 in order to make sure that the mould was filled up to the same level in all of the simulations performed.
2. The velocity magnitude at the level of Probe 1 was less than an infinitely small value (0.004 m/s). This was for ensuring that the system was equilibrated at the end of each simulation case.

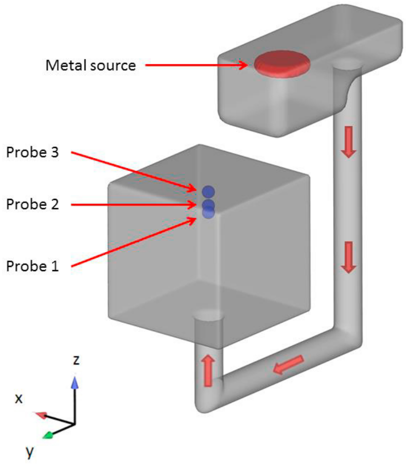

Figure 2: Simulation setup

A hexahedral mesh with a cell dimension equal to 2 mm was utilised for solving the mass, momentum and energy conservation equations. The mesh was confined to the open volume of the computational domain with an overlap length equal to 10 mm in order to maintain the computational cost within acceptable limits. The constructed mesh consisted of 1,566,000 cells in total. Symmetry boundary conditions were applied to all mesh boundaries, while a pressure boundary condition was applied to the z_{max} boundary. An overview of the simulation parameters and the metal properties considered is listed in Table 1. It should be noted that the mould was considered to be made of sand silica while the LM25 properties identified with an asterisk in Table 1 were considered temperature dependent and tabular data were used.

Table 1: Simulation parameters & LM25 properties

Simulation parameters		**LM25 Properties**	
Pouring temperature [°C]	720	Density* [kg/m^3]	2416
Mould initial temperature [°C]	25	Viscosity* [Pa·s]	0.00138
Air initial temperature [°C]	25	Specific heat* [J/(kg·K)]	1186
Heat Transfer Coefficient (LM25/air) [W/(m^{2}K)]	30	Thermal conductivity* [W/(m·K)]	70.153
Mould thermal conductivity [W/(m·K)]	0.7	Solidus temperature [°C]	550
		Liquidus temperature [°C]	611

The RNG model was employed for modelling turbulence [15]. During filling, the fluid momentum and continuity equations were solved and a first order method was employed for the evaluation of the fluid internal energy advection. The commercial CFD software FLOW-3D® [16] was used to complete this study. Air entrainment and surface defect concentration were evaluated using the corresponding Flow-3D models [17,18].

2.2. TOPSIS

In this study the evaluation of the alternative design solutions has been performed using the deterministic TOPSIS method [19]. TOPSIS relies on the concept that the optimal alternative should have the minimum distance from the Positive Ideal Solution (A^+) and the maximum distance from the Negative Ideal Solution (A^-). The steps of the TOPSIS method are briefly listed below:

1. Normalisation of the decision data.
2. Estimation of the weighted normalised decision matrix.
3. Determination of the positive and negative ideal solutions.
4. Calculation of the separation distance of each alternative from the ideal solutions.
5. Estimation of the proximity to the ideal solution.
6. Ranking of the alternatives.

Additional information on the implementation of the TOPSIS method can be found in [20].

3. Results & Discussion

The velocity profiles of the liquid LM25 during filling are illustrated in Figure 3 for evenly spaced timesteps (Basic Gating System/circular cross section). It can be observed that the maximum velocity magnitude is observed at the vertical pouring basin, as expected. With the exception of this part of the gating system, the maximum meniscus velocity does not exceed 0.5 m/s as suggested by Campbell [21]. Moreover, by observing Figure 3(d) and Figure 3(e), it is clear that the mass source has been removed within the time interval defined by the corresponding timesteps (t=16 s and t=20 s). It is evident that the liquid Aluminium has reached very close to an equilibrium stage at t=20 s, as the velocity magnitude is almost zero across the simulation domain. The simulation is being terminated once the conditions stated in the Methodology section have been satisfied.

An overview of the air entrainment and free surface defect concentration at the end of the filling process across the computational domain is illustrated in Figure 4 and Figure 5 respectively. It can be observed that the air entrainment is higher at the pouring basin due to the increased velocity magnitude and turbulence intensity at this area. On the other hand, as shown in Figure 5, the higher values of free surface defect concentration are located in the vicinity of the liquid metal free surface, as expected.

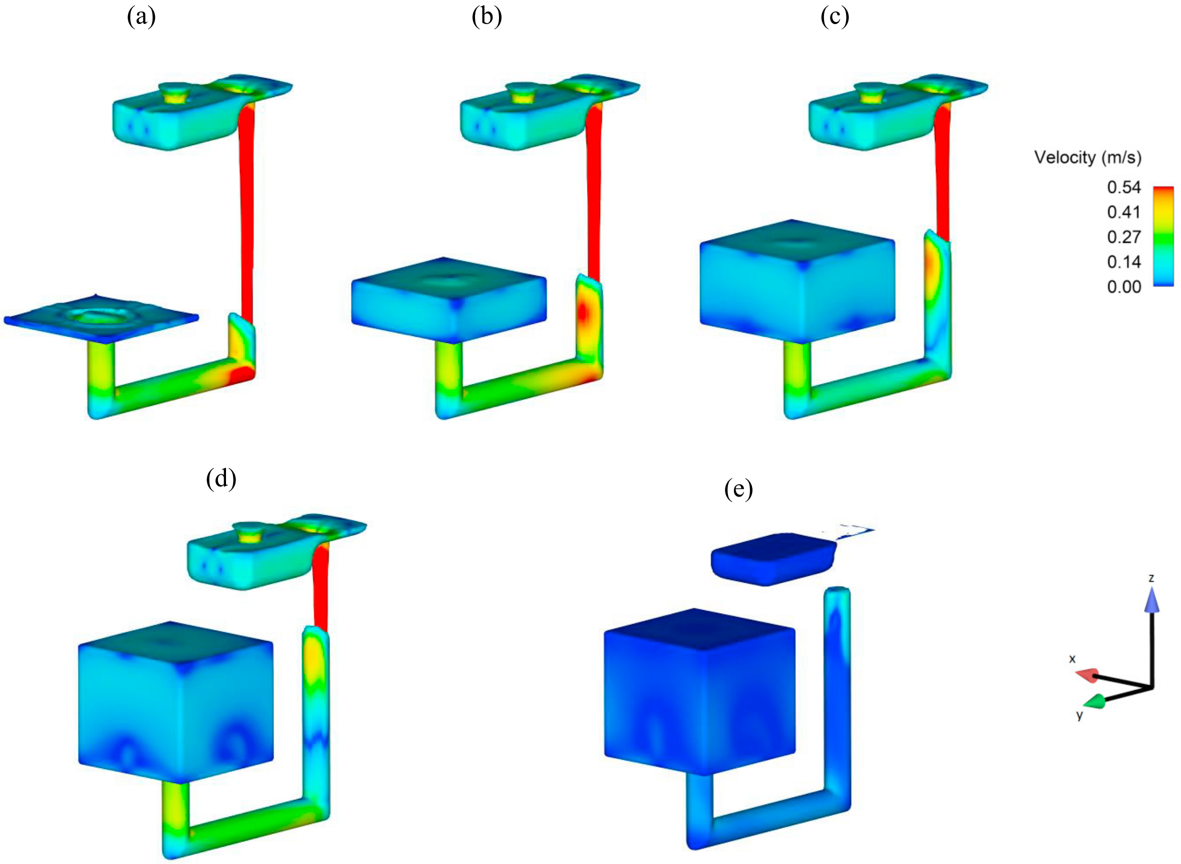

Figure 3: Velocity magnitude contours at t= (a) 4 s, (b) 8 s, (c) 12 s, (d) 16 s and (e) 20 s for the Basic Gating System Design with circular cross section

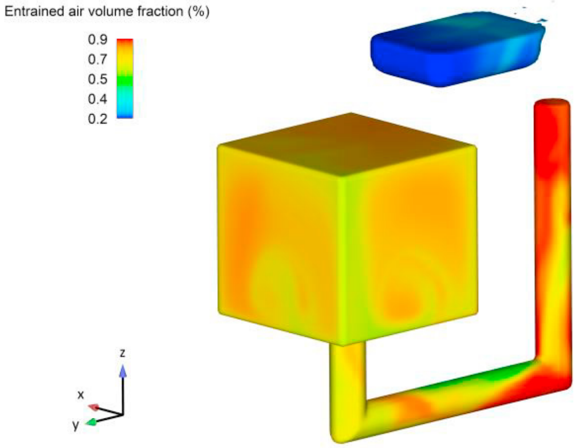

Figure 4: Entrained air volume fraction (Basic Gating System Design)

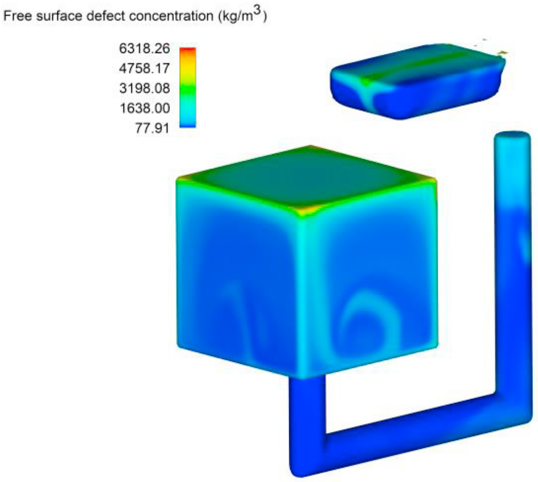

Figure 5: Free surface defect concentration (Basic Gating System Design)

The averaged values of air entrainment and free surface defect concentration (FSDC) were computed over the volume of the final product (cube) for each one of the designs considered. Moreover, the overall process energy was evaluated for each case according to:

$$Q = mc_P \Delta T \tag{2}$$

where m is the total mass of the liquid metal in the computational domain, c_P = 1186 J/(kg·K) the specific heat of Aluminium alloy LM25 and ΔT = 720 – 611 = 109 °C the superheat. The costs of the moulds considered were selected according to [22] based on the complexity of each mould design. The performance of each gating system design against each criterion is summarised in Table 2.

Table 2: Performance of gating system designs against set criteria

	Circular basic	**Rectangular basic**	**Circular with fillets**	**Rectangular with fillets**	**Circular inclined**	**Rectangular inclined**
Air volume ($\cdot 10^{-4}$ m^3)	8.956	9.438	8.557	9.678	9.274	9.98
FSDC (kg/m^3)	367.514	374.811	330.548	351.363	347.247	352.275
Energy (kJ)	2274.24	2276.61	2259.98	2261.60	2288.76	2289.70
Cost (USD)	1500	1500	1600	1600	1600	1600

The summarised information presented in Table 2 is indicative of the performance of each design considered against the decision making metrics. In most of the cases the *circular cross section with fillets* design appears to be a winner since it leads to reduced air entrainment and surface defect concentration. This is because the particular design assists laminar flow and minimises turbulence. Someone would expect that minimum turbulence should be observed for the *circular inclined* design; this is not the case because the liquid metal is also accelerated in the longitudinal direction (y-axis) besides the direction of gravity (z-axis). As a result, when the liquid metal impinges on the ingate, a high turbulence intensity region is generated; this leads to increased air entrapment and free surface defect concentration. An additional observation is that for all 3 basic concepts examined (basic/with fillets/inclined) the circular cross section performs better in terms of air entrainment and surface defect concentration. This is because the corners of the rectangular cross section impose more abrupt changes to the flow direction and consequently surface turbulence is intensified.

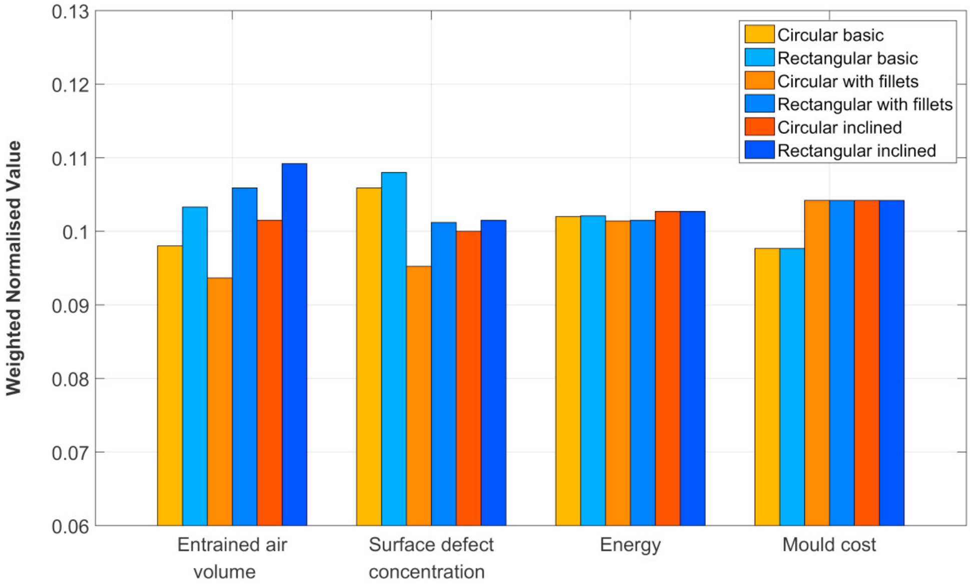

Figure 6: Weighted normalised values of the alternative gating system designs against the four evaluation criteria

In Figure 6 the weighted normalised values of the alternative designs, calculated via the TOPSIS method, are plotted for 4 different evaluation criteria, namely: (a) entrained air volume, (b) surface defect concentration, (c) energy and (d) mould cost. It should be noted that bars coloured with shades of blue and red correspond to rectangular and circular cross sections respectively. In this case, the 4 weights assigned to the corresponding criteria are balanced and equal to 0.25. With regard to all of the criteria under examination, with the exception of the mould cost, the *circular with fillets gating system* design appears to be a winner; the lower the score the more positive the impact.

Table 3: Weight distributions

	Entrained air volume	**Surface defect concentration**	**Energy**	**Mould cost**
wd_1	0.5	0.16667	0.16667	0.16667
wd_2	0.16667	0.5	0.16667	0.16667
wd_3	0.16667	0.16667	0.5	0.16667
wd_4	0.16667	0.16667	0.16667	0.5

The current investigation has been also expanded to the effects of various weight distributions between the criteria and 4 additional cases have been considered as listed in Table 3. The similarity index to the negative ideal solution (s^-), being indicative of the overall performance of each design alternative for 4 different weight distributions, is illustrated in Figure 7. The circular with fillets design appears to be the optimal selection for all the weight distribution variants with the exception of wd_4. This is because in this case a high weight value is assigned to mould cost criterion, with regard to which the particular design underperforms. An additional conclusion is that for all cases examined, rectangular cross sections are characterised by inferior performance compared to the corresponding circular ones.

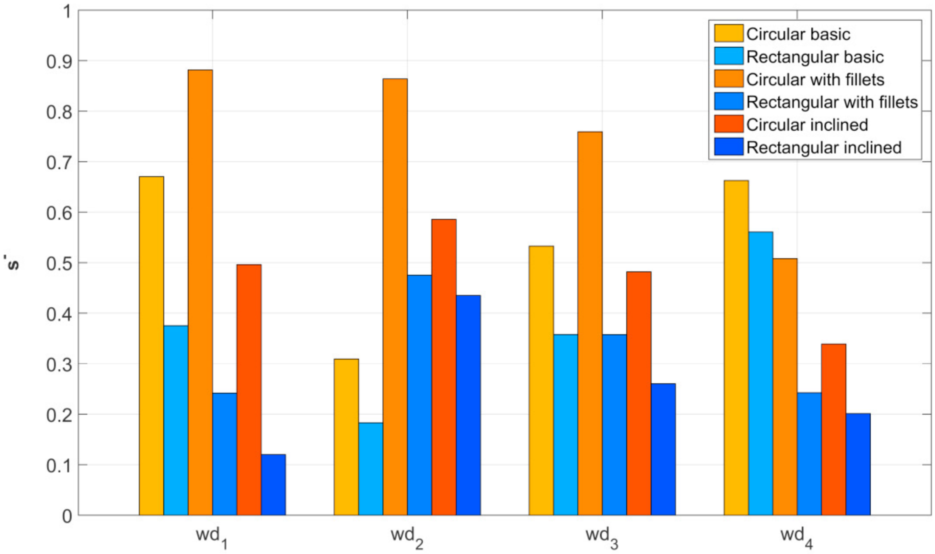

Figure 7: Similarity index to the negative ideal solution s^- of the alternative gating system designs for various weight distributions

4. Conclusions

The objective of this investigation is the development of a Multi-Criteria Decision-Making framework for the evaluation of the sustainability performance of casting system designs. Six gating designs were considered and ranked according to their sustainability performance and the quality of the final product. For this purpose, 4 main criteria were selected, namely: (a) air entrainment, (b) surface defect concentration, (c) energy and (d) mould cost. This Multi-Criteria Decision-Making investigation was performed by integrating Computational Fluid Dynamics (CFD) simulations with the deterministic TOPSIS method. The alternative gating system designs were compared between them for various sets of weight distributions while the optimum/poorest designs were identified.

Our results indicate that in most of the cases examined the *circular with fillets* gating system design should be favoured against the rest of the alternatives while circular cross sections should be used instead of rectangular ones in order to impede turbulence. The presented framework can be implemented as a tool for foundry engineers for the selection of the optimal casting system design given a number of alternatives with respect to set evaluation criteria and assist the decision-making process without having to perform a large number of costly and time consuming experiments.

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