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Energy and material efficiency metrics in foundries

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Abstract

Most of the current foundry processes are based on well-developed and established practices typical of mature technologies. Contemporary economic, environmental and societal developments have concurrently changed at an unprecedented rate the context where traditional metal casting methodologies have not really developed much over time. Consequently, significant challenges and opportunities arise. This work will present the founding metrics of a novel approach to metal casting with the development of a new philosophy (called "Small is Beautiful") aimed at tackling the current pressures on the industry with a focus on energy and materials' efficiencies and flexible production. Traditional and well-established parameters are presented and compared to new metrics defined from first principles and thermodynamic properties. All metrics are validated using industrial and scientific literature data of five sand casting plants melting different ferrous and non-ferrous alloys.

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1. Introduction

Metal shape casting is among the oldest manufacturing processes and its origins can be traced back to the prehistoric period of mankind. Over time its processes have developed in conjunction with new alloys. Well after the flourishing of the scientific revolution, metal casting has been long considered an art [1]. Probably because of its long history, the adoption of a more scientific approach has proceeded slowly and a more systematic analysis of the related complex engineering problems has been completed only a few years ago. For example, John Campbell's "Ten rules for good casting" is one of the most recent and significant achievements of this approach [2].

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However, resource scarcity, environmental pollution and demographic pressure on resources push the mature, energy intensive and highly competitive metal casting industry towards future challenges. “Small is Beautiful” is a new philosophy that intends to respond to these contemporary issues incorporating resource efficiency (both in material and energy terms) and flexible production since the beginning of the design process. Alongside the mentioned characteristics, other critical aspects, such as profitability and responsiveness to market needs are considered. Energy resilience is identified as the first step to address the mentioned challenges considering the energy intensive nature of metal casting. In the longer term, a more comprehensive and holistic approach implementing all aspects of sustainability [3] is envisaged. “Small is Beautiful” intends to support and promote both these future evolutionary steps, as depicted in Figure 1.

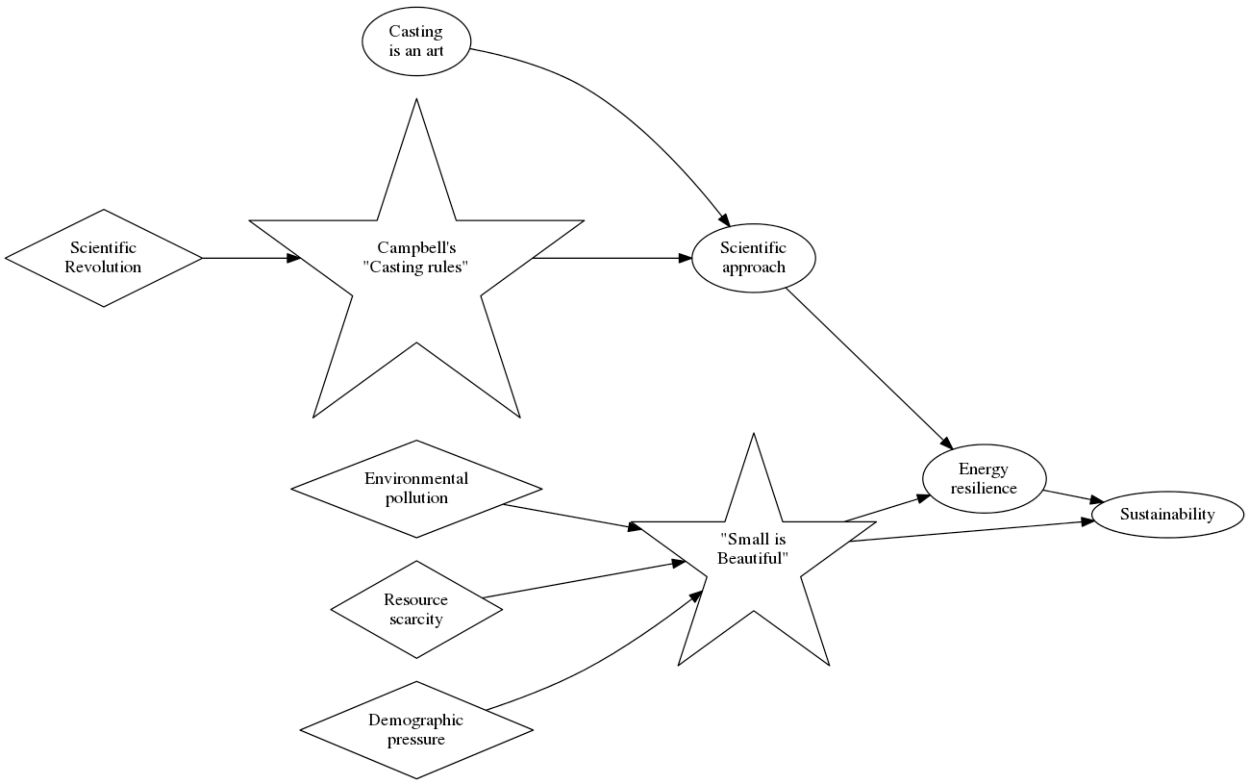

Fig. 1. Examples of historical metal casting development (elliptical elements) with two major (but not exhaustive) intellectual contributions (stars) and the relevant environmental pressures that generated them (diamonds).

2. The “Small is Beautiful” project

The first steps in defining this new philosophy were focussed on capturing practices and comparing energy and resource efficiency studying 80 foundries, contacting 60 and visiting 10 of them. About 100 enterprises and industry experts were interviewed and general energy data were collected. This survey revealed that usually foundries do not consider energy efficiency and emissions a key decision-making factor and thus do not monitor in detail energy consumption. In this area, the greatest interest of the foundry management is on the costs associated with energy bills. As a consequence, there is generally little knowledge on how to monitor energy efficiency and, where identified, major differences in practices between foundries have been recorded [4]. Thus, the need for a structured energy auditing framework [5] and an effective visualisation tool of measurements able to integrate with existing manufacturing systems [6,7] have been identified. An example of Sankey diagrams that can be obtained with the mentioned visualisation tool is shown in Figure 2.

A fundamental step to develop further and implement the framework of "Small is Beautiful" is the definition of energy and material efficiency metrics that could describe foundry processes and benchmark them in quantitative terms. This work will describe the metrics usually adopted in this context and will propose some new ones.

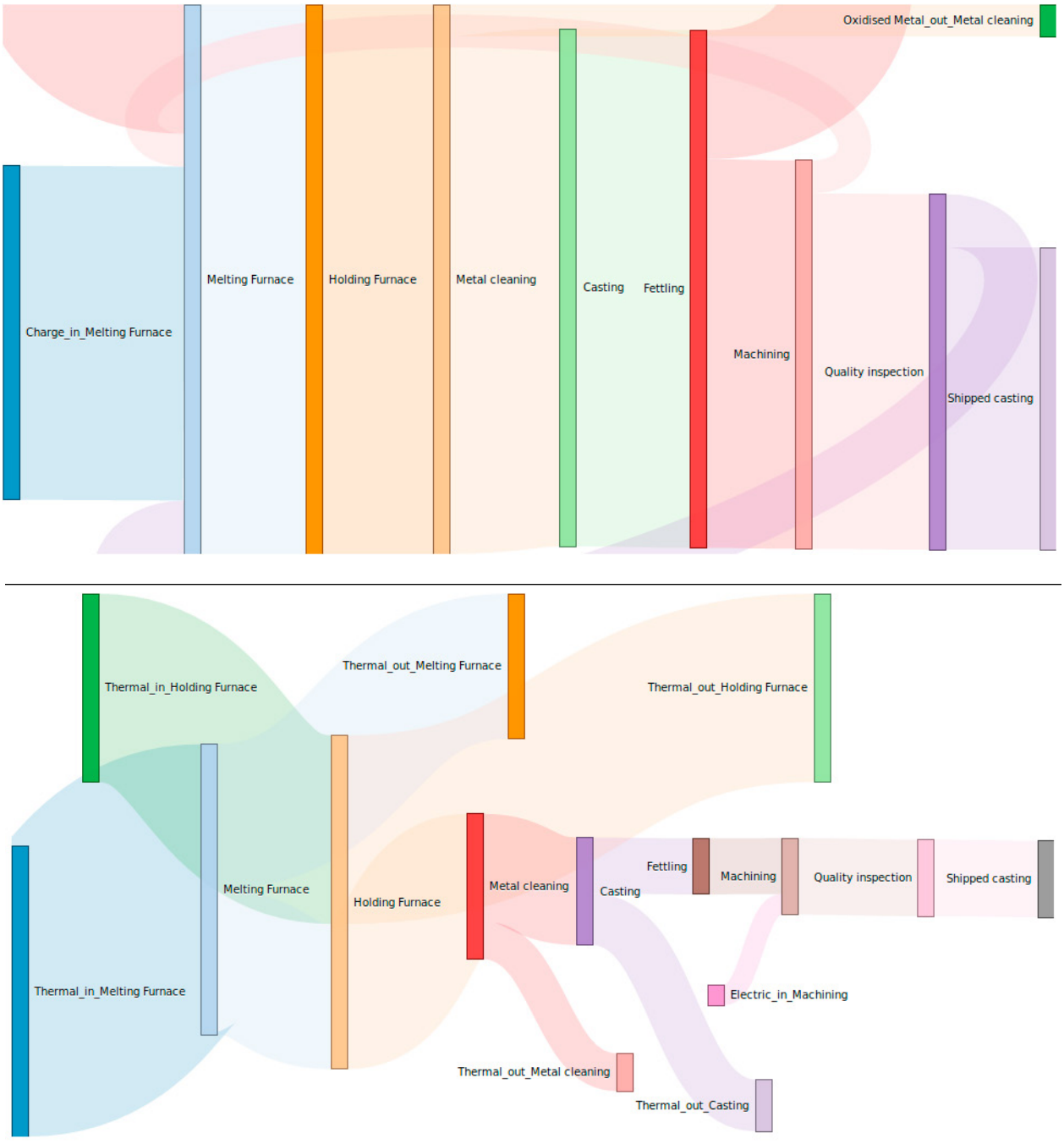

Fig. 2. Example of material (top) and energy (below) flows in Sankey diagrams of a metal casting foundry. The diagrams have been generated by the computer program developed for the "Small is Beautiful" project [7]. Material flows are expressed in kg and energy flows in GJ.

3. The shape casting process steps

Metal casting encompasses a large and diverse family of processes that can be categorised in different ways. For example, it is possible to identify two main groups of processes considering if the liquid metal fills the mould with or without the effect of additional pressure exerted externally [1] or if the mould is expendable or permanent. Notwithstanding the large variety of processes, it is possible to identify an abstract set of steps able to describe the vast majority of metal casting practices. Such generalised shape casting process steps are represented in Figure 3.

The first process step is melting the charge and any other form of recycled metal from later processes. A proportionally large amount of energy [8] is required to bring the metal beyond the melting point to a "superheat temperature" that is usually a compromise between optimal fluidity, a sufficient margin to certainly fill the mould before solidification and generation of oxides or dissolved gas [1].

Another energy intensive process (although not always necessary) is holding the liquid metal to accommodate different production rates or to allow the cleaning of the melt from impurities, oxides and dissolved gas. Although cleaning is conceptually another process, it may take place in the holding furnace. In parallel, a mould (made of sand, metal or ceramic material) needs to be prepared for the casting phase when the liquid metal is poured into it. During the previously described steps a non-negligible amount of thermal energy is rejected into the environment alongside a variable quantity of metal oxides that inevitably are generated.

With "finishing" a number of possible operations are intended. Finishing includes certainly the removal of gatings, runners and risers (i.e. fettling) necessary by design to create a sound product with minimal shrinkage and inclusion defects. The relevant metal removed may be recycled in the melting furnace. However, also machining is sometimes performed at this stage of the process and is another example of operations included in the general definition of finishing.

Before the finished product can be shipped, it is usually inspected in different ways with a relevant fraction of scrap that can be internally or externally recycled.

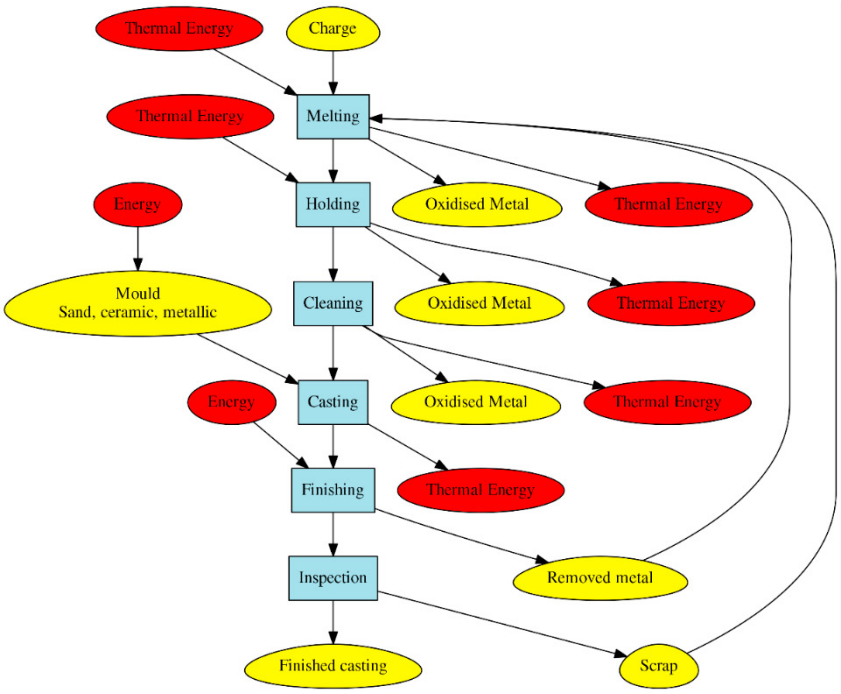

Fig. 3. Generalised shape casting process steps (in light blue) with the relevant main material (in yellow) and energy flows (red).

4. Energy and material efficiency metrics

With reference to the generalised process of Section 3, it is possible to define a number of metrics that describe the performance of foundries in terms of energy and material efficiency.

A relatively well-established parameter to compare the *overall* energy performance of foundries, both in the scientific literature and for the auditing of foundry sites, is the Specific Energy Consumption (SEC) [9,10]. However, considering the large differences between casting practices, SEC is mostly used to compare processes of ferrous materials melt with induction furnaces or aluminium alloys in resistance furnaces [8,9,11,12]. The advantage of this metric, that can explain also its success, is its simple definition that requires minimal, aggregate data from the plant that are almost always available. In fact, SEC is obtained dividing the total energy consumption (i.e. the total energy input $E_{in,tot}$) of the plant over a representative amount of time (usually one year) by the amount of good castings shipped to the customer m_s. Liaising with industrial experts of the field emerged that often SEC is loosely defined and calculated also against the total mass of metal melt over the representative amount of time m_m. To avoid this source of confusion, in this work two different metrics will be defined:

$$SEC_o = \frac{E_{in,tot}}{m_s} \tag{1}$$

and

$$SEC_m = \frac{E_{in,tot}}{m_m} \tag{2}$$

Although the SEC parameters are simple to calculate, their main limitation lies in not being rigorously defined in thermodynamic terms, i.e. they are dimensional parameters (usually expressed in MJ/kg or kWh/t) that do not take into account the thermodynamic properties of different alloys to be melted. This also explains why they are not usually used to compare processes melting significantly different alloys. In fact, the large amount of energy required for melting (that dominates the overall energy input of the plant [8]) is dependent on the alloy-specific thermodynamic properties (i.e. its specific enthalpy rise to the liquidus point Δh_l). In symbols, the ideal, minimum energy input necessary for any casting process $E_{in,id}$ is

$$E_{in,id} = m_s \Delta h_l \tag{3}$$

Hence, it is possible to define the non-dimensional overall process efficiency η_o as follows

$$\eta_o = \frac{E_{in,id}}{E_{in,tot}} \tag{4}$$

that is able to take into consideration the thermodynamic properties of the alloy to be melt.

However, in Section 3 it has been explained that every casting process needs to bring the metal alloy to be cast at the “superheat temperature”, beyond the melting point. Since this aspect is specific of the melting process and it is not included in η_o and considering the fundamental importance of the melting phase, another metric, the melting efficiency η_m is then defined

$$\eta_m = \frac{m_m \Delta h_{sh}}{E_{in,m}} \tag{5}$$

where Δh_{sh} is the enthalpic rise of the alloy to the superheat temperature and $E_{in,m}$ is the total energy spent during the melting phase.

If more equipment-specific data can be collected form the plant, a breakdown of the total energy input for each phase can be calculated (e.g. according to the generalised classification of Section 3) and the relevant fraction of the total energy input φ_i, can be calculated for each i-th phase:

$$\varphi_i = \frac{E_{in,i}}{E_{in,tot}} \tag{6}$$

For example, for the melting phase it holds

$$\varphi_m = \frac{E_{in,m}}{E_{in,tot}} \tag{7}$$

The typical material efficiency metric used in metal casting is yield [8] that describes the material loss during a certain process, calculating the ratio between the mass before and after it. Unfortunately, also this term is often adopted loosely and generally speaking the boundaries that define its calculation are seldom clearly defined. Ways to circumvent this shortcoming are the definition of *overall* yield (where the process from melting to shipping is included) or *mould* yield (where only the fettling operations are included in the definition). Another way to deal with the potential ambiguity is to consider the overall yield as an operational metric and defining it as the Operational Material Efficiency (OME) defined as follows [5]

$$OME = \frac{m_s}{m_m} \tag{8}$$

This last parameter will be considered in this work as a measure of the overall process material efficiency.

The selected metrics have been designed according to a generalised shape casting process and thus, do not include any information about a specific metal casting practice. For this reason, they must be used with care when comparing processes belonging to different families of processes (e.g. sand casting versus investment casting).

5. Validation

Industrial and scientific literature data of foundries producing castings of different alloys have been used to validate the metrics defined in Section 4. The following five *sand casting* processes have been considered:

- a state-of-the-art plant producing cast iron (CI) automotive parts;
- ductile iron (DI) castings for infrastructure components;
- aluminium alloy automotive parts using a gravity process (AG);
- aluminium alloy automotive parts using a low pressure process (ALP) – known also as the Cosworth process;
- copper alloy (aluminium bronze – AB) parts for the maritime industry [8,13].

The thermo-physical properties of the cast metal alloys have been calculated according to the data published by Mills [14].

Figure 4 shows a comparison of the processes according to the "traditional" metrics (i.e. SEC_o, SEC_m, OME) together with the fraction of the energy spent for melting φ_m, as defined by Equation (7). It is visible the effect of the OME on the difference between SEC_o and SEC_m: the lower the material efficiency, the larger the difference between the two specific energy metrics. The ferrous processes appear to be more efficient (because, for example, they do not require any holding time and show higher mould yield) and it is notable how the CI foundry has been designed very efficiently to basically require energy only for melting ($\varphi_m = 0.96$) recording very low specific energy

consumption. However, the values of SEC do not immediately tell how close to the theoretical maximum the process is running.

Figure 5 compares the new metrics defined in this work by Equations (4) and (5) with the traditional specific energy consumption. To ease the comparison, the inverse of SEC_o and SEC_m have been represented so that a more efficient foundry will be represented by a higher value of η_o and η_m and also of the inverse of SEC_o and SEC_m. It should be clarified that both SEC_o and SEC_m are metrics that describe the *overall* performance of the plant from two different points of view and, thus, they should be compared to η_o only. The melting efficiency η_m is an important, additional parameter that helps in understanding how well the fundamental melting process performs.

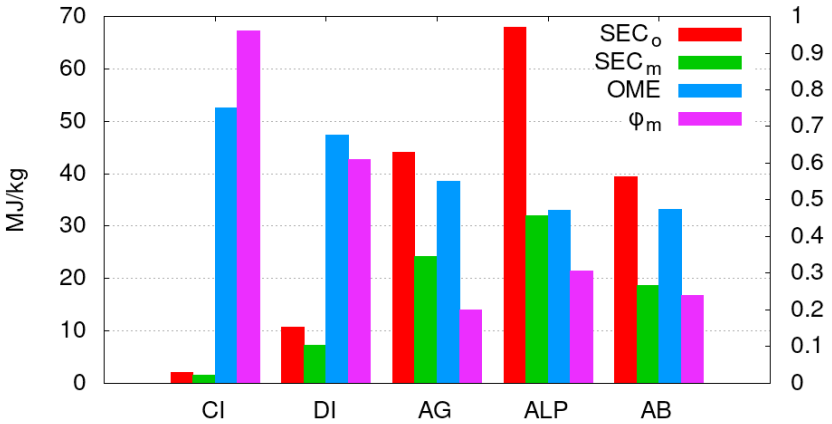

Fig. 4. Traditional energy e material efficiency metrics used to compare sand casting foundries producing cast iron (CI) automotive parts, ductile iron (DI) infrastructure products, aluminium alloy automotive parts with a gravity process (AG), aluminium alloy automotive parts with a low pressure process (ALP), aluminium bronze (AB) maritime parts. SEC: Specific Energy Consumption; OME: Operational Material Efficiency; φ_m: melting energy fraction.

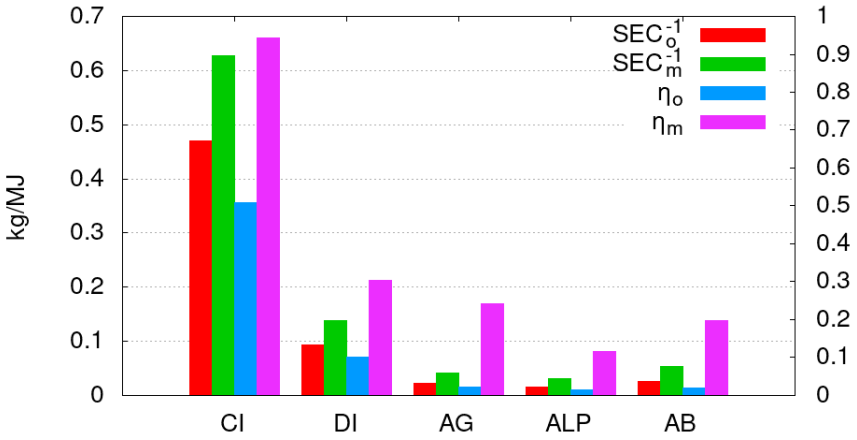

Fig. 5. Comparison of the proposed energy efficiency metrics (η_o and η_m) with the traditional counterparts ($1/SEC_o$ and $1/SEC_m$) for five sand casting foundries producing cast iron (CI) automotive parts, ductile iron (DI) infrastructure products, aluminium alloy automotive parts with a gravity process (AG), aluminium alloy automotive parts with a low pressure process (ALP), aluminium bronze (AB) maritime parts. SEC: Specific Energy Consumption.

The comparison shows that although the SEC metrics do not include any information about the thermo-physical properties of the different alloys, they still seem able to correctly compare the performance of the different plants no

worse than the rigorously defined η_o. Further comparisons with other alloys may confirm this statement. However, it is interesting to see quantified by a scientifically defined metric (η_o) how intrinsically inefficient metal casting is and, thus, how difficult it is to design such a complex process in an energy efficient manner when compared to its theoretical minimum. Even the state-of-the-art CI foundry plant barely exceeds 50% overall efficiency, with more standard processes designed for aluminium and copper alloys sitting around or below the 2% mark.

6. Conclusion

A new philosophy to transition metal casting towards more efficient and sustainable practices, addressing also current and future competitiveness issues, was presented. The definition of energy and material efficiency metrics was discussed for a generalised shape casting process. Traditional, well-established energy metrics were questioned about their ability to correctly compare processes of the same family (e.g. sand casting) but melting significantly different alloys. Hence, new energy metrics addressing this issue and others able to assess the melting phase were defined and compared to the traditional ones using real industrial data as well as scientific literature sources. A well-established material efficiency parameter was also defined and validated.

The mentioned validation appears to confirm that the traditional energy efficiency metrics, although not rigorously defined in thermodynamic terms, are suitable to compare also different metal casting alloys. However, further investigations with more alloys would strengthen this conclusion. The new metrics improved traditional parameters to represent a clear benchmarking tool against the theoretical minimum energy required by the overall process. Moreover, other new metrics were defined to structure a sound auditing framework in foundries.

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