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Energy Efficient Casting Processes

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Abstract

Metal casting is one of the most energy intensive manufacturing processes that has developed along the evolution of mankind. Although nowadays its scientific and technological aspects are well-established, in the context of future resource scarcity and environmental pollution pressures, new studies appear necessary to describe the “foundry of the future” where energy and material efficiency are of great importance to guarantee competitiveness alongside environmental protection. In this chapter, both managerial and technical good practices aimed at implementing energy efficient casting processes are presented alongside a few examples. The “Small is Beautiful” philosophy is presented as a systematic approach towards energy resilient manufacturing and, potentially, sustainability in the long term. Thus, this chapter aims at providing an overview of the different aspects comprising the state-of-the-art in the industry and examples of research themes in academia about energy efficient casting processes.

Keywords

Casting; Foundry; Sustainability; Energy efficiency

1. Introduction

Shape casting is a manufacturing process characterised by its energy intensive nature (i.e. the use of a large amount of energy per unit product for the core activities) and a long tradition where technological improvements progressed alongside the history of mankind [1]. This work aims at discussing the future of the foundry industry while dealing with resource scarcity and environmental pollution pressures: two important future challenges. Energy efficiency addresses, in the first instance, these challenges although a more comprehensive approach is envisaged in the longer term where, sustainability is implemented in metal casting and will include economic, environmental and societal aspects [2].

The United Kingdom metal casting industry can be broadly representative of the energy efficiency in a typical developed country with £2.2 billion turnover and

17000 jobs [3] in 422 foundries (intended as production units active in 2015) [4]. In comparison, for example, France and Germany show a comparable number of production units (namely, 413 and 588) [4]. Furthermore, the ratio of inhabitants per metal casting production unit I_f results fairly constant among several developed countries like the mentioned UK, France, Germany, USA and Canada (Table 1).

Table 1. Thousand of inhabitants per metal casting production unit I_f in some developed countries (2015 data). The UK appears to be broadly representative of developed countries with a significant foundry industry showing a comparable I_f factor to Germany, France, the USA and Canada. Data source: population [5], plants [6].

Country	Population (thousands)	Number of metal casting plants	I_f
United Kingdom	65 128.86	422	154.33
Germany	81 686.61	588	138.92
France	66 624.07	413	161.32
USA	320 896.62	2380	134.83
Canada	35 848.61	183	195.89
Italy	60 730.58	1085	55.97
Spain	46 447.7	128	362.87
Japan	12 7141	2085	60.98

A study conducted in the UK showed that, although aggregate data of energy and material consumption is recorded in foundries, most often there is no protocol to monitor the energy consumption along the process [7]. The mentioned aggregate data are usually used to control utility billing, to analyse broadly the performance of the plant and to learn what practices are more effective. One of the main reasons for such practice, as identified by the mentioned study, is that a significant number of foundries do not measure the energy consumption of their installed systems comprehensively [7].

On the other end, the UK Government (through the Department of Energy and Climate Change) has set a target for the foundry industry in terms of specific energy consumption of 25.7 MJ/kg by 2020 although the average figure for the sector in 2013 was 55 MJ/kg [7]. Significant improvement in terms of energy efficiency is thus expected in the short-term by the sector.

In this chapter, the fundamentals of a generalised cast shaping process are presented in Section 2. Section 3 and 4 will discuss how energy efficiency can be achieved though (respectively) management practices and technological improvements. Finally, Section 5 will present real-life examples of energy efficient metal casting and Section 6 the “Small is Beautiful” philosophy developed taking into account material and energy resilience in casting manufacturing processes. The content makes the reader able to understand the fundamental problems, the industrial state-of-the-art and examples of the on-going academic research about energy efficient casting processes. Figure 1 summarises broadly the content of this chapter.

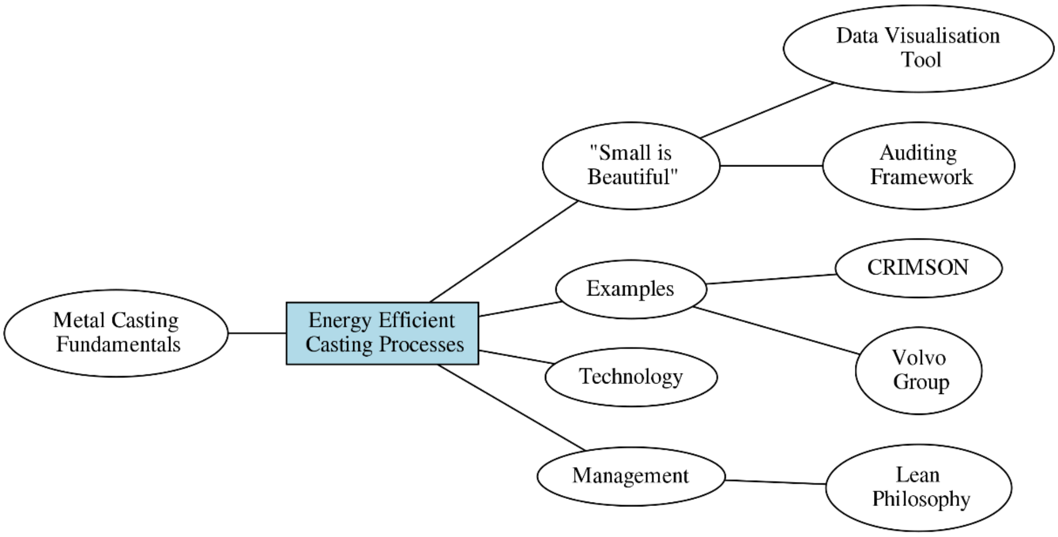


Fig. 1. Main sections comprising this chapter.

2. Metal casting fundamentals

Modern metal casting includes different types of processes with specific characteristics that can be classified in different ways. One example of broad classification is identifying two main groups of processes based on the condition whether the liquid metal fills the mould with or without the effect of additional pressure exerted externally (besides gravity) [1] or if the mould is expendable or permanent [8, 9]. Analysing all the casting processes from an abstract point of view, a number of generic, common sub-processes can be identified as depicted in Figure 2.

The first process step is melting the charge and any other form of recycled metal from later processes. A proportionally large amount of energy [10] 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 gases [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 gases. 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 the gating, 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.

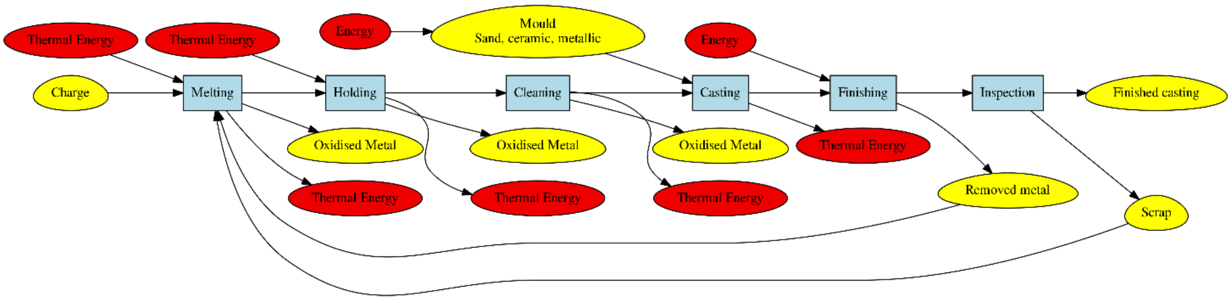


Fig. 2. Generalised shape casting process steps (in light blue) with the relevant main material (in yellow) and energy flows (red).

3. Energy efficiency through management

As well as technical means (described in Section 4), management good practices are another, complementary, effective way to reduce waste and improve the metal casting process in terms of energy efficiency. This section presents initially the management practices in the context of foundries and then focusses on the discussion of the promising lean thinking philosophy. Finally, practical examples are provided in the last subsection.

3.1 Management practices in Foundries

Profit margins are usually relatively small in the metal casting industry, limiting the opportunities to invest in more efficient equipment [11]. For this reason, better foundry management practices are often even more desirable than technological improvements. Moreover, although significant research efforts have been directed towards energy efficiency measures, there is still a substantial potential in research about management of resource efficiency [12]. Similar energy efficiency management practices are applicable to companies of different size, but the relevant skills available and goals determine a different decision making process.

Smaller firms (that represent a significant proportion of foundries) have limited knowledge of energy efficiency measures [13, 14] and Small and Medium Enterprises (SMEs) do not consider investments with a payback time longer than 2-3 years [14]. On the other hand, larger enterprises have been found to struggle more to effectively implement energy management practices in general [15]. Barriers hampering such enhancements comprise difficulties to easily communicate with the high-level management and complicated production processes and organisational structures [15].

Beyond these considerations, it appears that management practices in energy efficient casting are not well developed. For example, a research conducted in Sweden showed that almost half of the Swedish foundries do not have a long-term energy plan and that energy management can be considered successful only in about one quarter of them [16]. Next section will discuss one prominent management technique significantly popular also within foundries: the lean manufacturing philosophy and it will be followed by some examples of its practical implementation in the metal casting industry.

3.2 Lean manufacturing concepts in foundries

The introduction in the scientific literature of the lean manufacturing philosophy can be traced back to 1990 with a study by Womack in the automotive field where a set of techniques adopted by Toyota Motors, focussed on quality and productivity, were highlighted [17]. This philosophy, that is meant to encompass every part of the enterprise, aims at boosting competitiveness reducing costs, maximising quality and minimising waste and lead time [18]. Waste is considered under several different aspects according to the “lean” point of view: defects, waiting, unnecessary processing, overproduction, movement, inventory, unused employee creativity and complexity [19]. All these aspects are targeted by lean thinking.

The further popularity of the lean paradigm in many different types of industry and service has as a common trait, besides the mentioned principles, the “lean culture” that must permeate fully the enterprise (and the mind-set of all its employees) rather than being a mere set of tools to be applied on the shop floor [22].

In the context of the foundry industry, it is possible to identify all key aspects of the lean philosophy. Considering waste, for example, defects are products scrapped, replaced or reworked not only during the final inspection phase, but anywhere along the process described in Figure 2. Waiting can be represented by the holding phase if it has been introduced to accommodate capacity bottlenecks, but generally speaking it can be the result of unbalanced lines, stock-outs or equipment downtime [19]. The typical unnecessary processing in metal casting is the fettling of sub-optimal gating and risers or as a result of far from net-shape forming processes. Overproduction can be generated by the temptation to take advantage of economies of scale and manufacture products for which there are no orders to avoid the long setup times (with the associated costs and additional energy consumption) required in foundries with intermittent production. Excessive movement can occur in foundries with sub-optimal layout that can waste substantial amounts of energy in sensible heat while increasing also the lead time. Inventory “waste” is typical of traditional foundries where large amount of stock is present [20, 21] mostly to avoid intermittent production and its long setup times. The lack of involvement of employees and their creativity is a general problem that has no peculiar manifestation in metal casting industries. Holding time can be in some cases a good example of complexity "waste" in foundries.

Moreover, efficient production and environmental impact (of which energy consumption is a considerable contributor) are linked together by the energy intensive nature of the process that is also strictly regulated [11]. Thus, although the implementation of environmentally friendly technologies does not add directly value to the product (and, for this reason, it would be in contrast with the lean philosophy) [23], the synergistic role of lean and environmental actions has been proven successful for the competitiveness of foundries [24]. The combined approach towards quality and environmental protection has been observed also by statistical observations where adopters of the ISO 9000 standard were more inclined to implement also ISO 14000 (that standardises Environmental Management Systems – EMS) [25]. Moreover, in 2011, ISO 50001 was published to establish the requirements for Energy Management Systems (EnMS) and it was structured in a similar way of ISO 14001 to allow the potential integration of EnMSs within EMSs [26]. The implementation model of EnMSs follows a simple sequence of tasks in a flow-chart fashion, as shown in Figure 3.

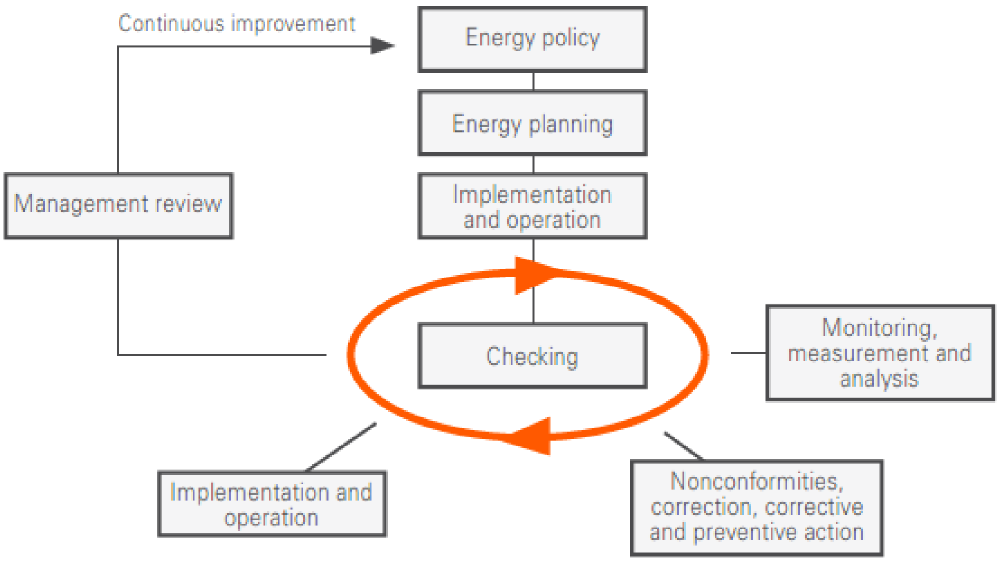


Fig. 3. Implementation model of ISO 50001:2011 [26].

3.3 Examples of lean implementation in foundries

The practical implementation of lean philosophy in metal casting industries can vary significantly considering the various unique combination of products and processes typical of this industry. For example, Torielli *et al.* proposed a framework for the synergic implementation of lean and environmental (i.e.

“green”) practices [11]. Figure 4 shows the relationship between the different elements comprising the framework.

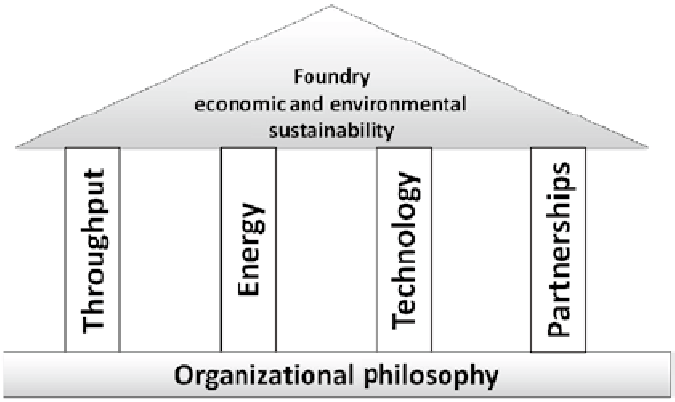


Fig. 4. Arrangement of the elements comprising a framework to implement lean and green practices [11].

Consistently with the “cultural” spirit of the lean paradigm, at the base of the framework sits the organizational philosophy that must involve employees at any level and must become the natural mind-set. Four pillars are based on the mentioned philosophy: throughput improvement, energy efficiency, innovative technology and community partnerships.

Improved throughput is achieved minimising scrap and processes that do not add value to the product, e.g. making scrap repair or welding unacceptable and, thus, unavailable in the foundry. This does not only streamlines the process steps (reducing operating costs, energy consumption and operating time) but also promotes the early detection of issues that generate scrap. Another means to improve throughput is the maximisation of Operational Material Efficiency (OME) that is the ratio between the mass of shipped castings to the customer over the mass of melted metal over a representative time span [27]. Such maximisation can be achieved making sure that the process is under control and designing to the nearest net shape possible, optimising size and location of risers and gating [28, 29]. To accomplish this last task, accurate computer simulation programs are very useful. Any improvement of OME will not only have a positive impact on the finishing and melting phases of the foundry process but, in an environmental perspective, will also reduce the embedded energy of the final product that includes also the energy necessary from mining onwards [11].

Energy efficiency can be pursued tracking the energy flows in the process. Interestingly, it has been confirmed that improvements in the energy consumption, alongside other lean manufacturing measures, determine a reduction in costs [30, 14].

Innovative technologies may be necessary to improve significantly the added value or the efficiency of the foundry (see Section 4). Financial sustainability of such measures is sometimes a barrier for their implementation or an important factor in the decision-making process among a number of options [11].

Community partnerships are described as the process with the highest potential concerning the environmental performance. They can help meet regulations as well as identify synergies with other industries that use waste products for their processes [11].

Another example of implementation of the lean philosophy in a foundry has been described by de Oliveira and Pinto [31]. The plant considered is a sand casting process melting ferrous alloys located in Brazil and producing parts for infrastructures, mining and cement industry as well as transport. After having mapped the process, a model in a simulation software has been created and validated against the mass of castings produced in one month. Then line balancing and layout improvements were sought using the created model [31].

Also Hari Priya *et al.* applied lean principles to a sand casting plant aiming at reducing lead time [32]. The goal has been reached using Value Stream Mapping (VSM): a material flow representation that highlights the locations where waste is produced [11]. VSM usually do not represent waste streams or ancillary material flows although it includes also the flow of information [11, 33]. When the full material streams in conjunction with the energy flows are represented, VSM takes the name of Green Value Stream Mapping (GVSM). This is a powerful tool to understand and analyse thoroughly the process or to communicate with partners or stakeholders. A further extension of GVSM would be the inclusion of embedded energy streams that allow to perform life cycle analyses [11].

The analysis by Hari Priya *et al.* implemented also 5S in the foundry [32]. 5S contributes to the lean paradigm in organising systematically every part of the shop floor (i.e. “the right thing in the right place at the right time”) [11] to easily identify waste as well as make evident any oversight or malfunction. 5S stands for Sort, Straighten, Shine, Standardise and Sustain (although also Safety it is usually added as sixth element) [11].

Using VSM and 5S Hari Priya *et al.* identified the opportunity to eliminate a thermal cycle aimed at stress relief and extended the cooling time of the castings in the mould. An improvement in rationalising the number of material grades available was also identified [32].

From the examples presented, it is clear that lean manufacturing techniques are effective and essential contributors to the development of an energy efficient foundry industry that preserves its competitiveness. The various lean tools can be chosen and adapted (also in the form of comprehensive frameworks) to the large variety of unique implementations of metal casting enterprises, maximising the benefits of technological improvements (if present) that will be described in the next section.

4. Energy efficiency through technology

Plant technical improvements are sometimes one of the first methods considered to increase energy efficiency or comply with environmental regulations. Although it is possible to obtain significant improvements by means of management actions in the foundry (as exemplified in Section 3), there are cases where technical enhancements are necessary to achieve certain levels of energy efficiency.

With reference to Figure 2, the first main process in metal casting is melting. Furnaces usually adopted to perform this task are cupola, induction, gas tower or gas crucible furnaces. Cupola furnaces extract heat from the combustion of coke, whereas electric induction furnaces induce a variable magnetic field through the charge that generates eddy currents dissipated into resistive heating. Finally, gas tower and gas crucible furnaces are both based on the combustion of natural gas with the former designed to accommodate higher production rates. The different types of furnace determine a different impact on the total energy consumption. For example, a study performed in Italy and focussed on the steel industry, has revealed that cupola furnaces contribute to about 50% of the overall foundry energy consumption, whereas electric induction furnaces account up to 70% [34]. At the same time, surveys and case studies have confirmed that induction furnaces are more efficient than cupola furnaces in the steel industry [35, 10].

A fundamental step of the metal casting process is pouring molten metal into the mould to shape it as necessary. Liquid metal must be brought at the correct temperature to ensure good fluidity and adequate filling of the mould. Both liquid metal quality and the pouring technique are important aspects to control, minimise or eliminate defects in the castings [1]. Metal fluidity is generally proportional to the liquid temperature and the necessary “superheating” (i.e. heating the alloy beyond its liquidus temperature) must be reached before pouring. Typical problems stemming from insufficient superheating are the incomplete filling of the mould, misruns, blow holes and chills. However, too-high superheat temperatures will determine excessive shrinkage of the casting, penetration of the metal into the mould (in sand casting processes), veining and scabbing [9]. An optimal superheating temperature has, thus, a twofold benefit: a reduction of defective castings and a reduction of energy consumption [34].

Considering that melting is typically the most energy consuming phase of the entire process [10], relatively small improvements determine significant energy savings. As previously explained, the superheat temperature (and the relevant fluidity of liquid metal) have a significant influence on the castings soundness and therefore, although it has a notable impact on the energy consumption of the melting phase, it cannot be easily reduced.

Metal pre-heating is not a necessary step but it can improve the energy performance of the entire process. Not only it provides a direct reduction of energy consumption [27], but it can be also used as the first, easier step to implement waste heat recovery. A typical industrial example of practices that take advantage of pre-heating is recovering thermal energy by cooling the hot, flue gas of the furnace to pre-heat the charge [27]. Usually, pre-heating involves relatively low-grade heat recovery that can provide a tangible benefit to the overall performance of the plant when designing the pre-heating and melting processes as physically close as possible.

Among the different types of melting furnaces, the electric induction is usually the most efficient with reported melting efficiencies near 75% [27]. However, coreless units are more suitable for primary melting because channel induction furnaces require a liquid metal charge [9]. Considering that a significant part of foundries are SMEs, their typical production method is batch or semi-batch production where coreless induction furnaces perform well [34]. One method to improve the efficiency of induction furnaces is increasing their operating frequency provided by the utility network, because it determines a consequent increase of power density. In turn, this enables the usage of smaller crucibles reducing heat loss.

Investing some energy (with the other relevant costs) to clean the scrap before re-melting is a good practice when considering the consequent energy savings to obtain good quality of liquid metal. In fact, the quality of material used to charge the melting furnace has been found to have an important impact on the overall energy consumption [34, 36] both by improving the furnace performance and the OME. Another good practice is to minimise the time and operations to open the furnace to reduce the sensible heat losses. Moreover, this represents another opportunity to recover waste heat [34, 27].

Similarly, the necessary cooling of electric induction furnace coils (usually at about 40-45°C), is another opportunity to recover heat for preheating purposes. Better insulated furnaces also have considerable impact on energy consumption [34]. Correctly trained operators can also improve efficiency in the region of 10% [27].

Holding liquid metal is not necessary and depends on the plant layout and on the process. It is another energy intensive step that requires to supply heat for a prolonged time to keep the charge at the desired temperature before pouring. Minimising the holding time is an important energy efficient measure and, if possible, it should be brought down to zero removing this unnecessary step according to a lean-thinking approach (as given in Section 3.2). In the cases when it is not possible to remove a holding phase, furnaces with advanced insulating materials and well-maintained can contribute significantly to reduce energy consumption [34].

In expendable mould processes, mould making requires notable quantities of energy input. It has been estimated that the whole sand system can contribute to about 20% of overall energy consumption in a foundry [34]. Improvements, such as novel sand CNC machining that do not require patterns to generate moulds [37] can clearly reduce energy consumption and cycle time. Automation is another option to improve productivity and energy efficiency keeping the process under control and potentially reducing material waste.

Fettling (i.e. removing risers and the gating system) when considered together with machining, can generate as much as 75% of the total scrap [27]. However, machining is an optional process (sometimes not carried out “in-house”) and, generally, fettling dominates clearly in terms of material loss between the two phases. As discussed in Section 2.3, the OME has a significant impact on the energy efficiency of the process, first of all because the material removed had been already melted. Hence, any design optimisation of the risers and gating system has a significant impact on energy and material efficiency.

Also the heat treatment phase is not necessary and is dictated by the mechanical properties of the product and the foundry equipment. Also in this case, heat treatment can be carried out by third parties. There is a significant variability in the characteristics of heat treatments and the relevant energy consumption can change notably. Moreover, a suboptimal control on this process phase can generate defects with relevant rejections [1].

As mentioned previously in this section, surface cleaning is important for the recycling phase determining significant benefits in terms of energy consumption. Moreover, this phase is necessary also to obtain the required level of quality of the finished product.

Factory services necessary to run the production are another cause of energy consumption that can be analysed [34]. Heating and cooling of the environment, compressed air systems and lighting are all common auxiliaries in foundries.

A significant reduction of energy consumption can be obtained with relatively modest improvements in these auxiliaries, despite their smaller contribution to the overall energy consumption [38]. For example, compressed air systems, although often adopted in manufacturing plants, are not well understood in terms of cost and, thus, on energy consumption [12]. Leaks are the major cause of supply losses in compressed air systems and it has been estimated that as little as 10-20% of the compressor input energy reaches the point of use [12, 34]. Improvements in this area comprise leak repair, upgrading the piping to a more efficient system or correct compressor sequencing. It has been identified that some metal casting firms do not realise the significant impact of auxiliaries on the overall performance [38].

Lighting often offers opportunities for energy efficiency improvements. Natural illumination should be maximised and the complementary role of artificial lighting should be promoted using state-of-the-art solutions like LED (that can determine up to 70-80% of reduction in costs [34]).

5. Examples of energy efficient casting implementations

A first example of energy efficient casting system is the CRIMSON process, currently developed at Cranfield University. The Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) process was designed with the purpose to minimise energy losses while improving the quality of the final product. One peculiarity of this system is that the charge is sufficient only to fill a single mould and it is melted within a crucible in an induction furnace. Then, the crucible is quickly transferred to the computer controlled up-caster (located close to the furnace) where the mould is filled counter-gravity controlling accurately the flow regime of the liquid metal.

The system is designed for energy efficient operations with minimal heat losses, no holding time and a high-efficiency induction furnace. The quick and simple procedure minimises oxide formation and gas dissolution that, together with the controlled filling process, produces castings of excellent quality as well as does not require additional steps to clean the liquid metal. Another important peculiarity of CRIMSON is the use of high quality, pre-alloyed metal as charge. Moreover, the gating system is significantly reduced in comparison with a conventional process with no need for the pouring basin and the down-sprue (Figure 5). This turns into a significant advantage during the fettling and machining processes (as discussed in Sections 2 and 3).

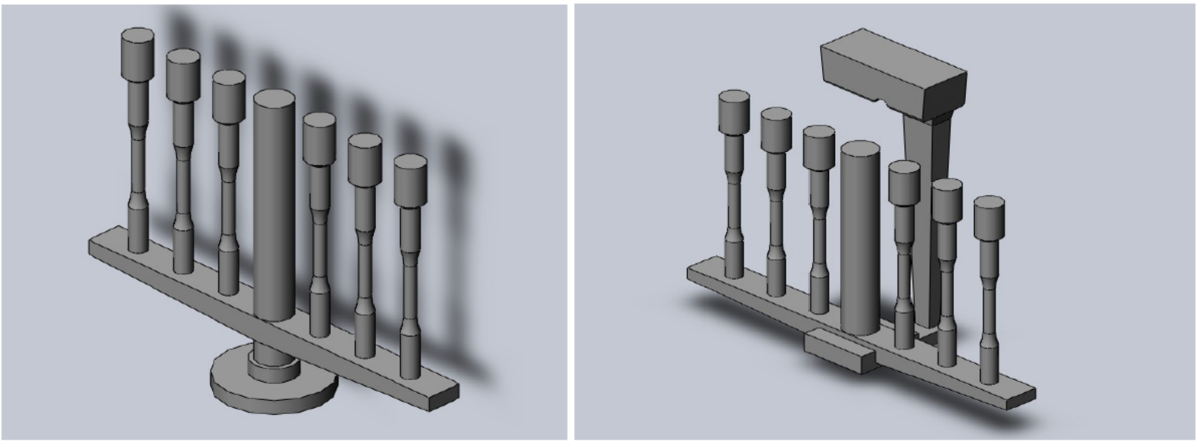
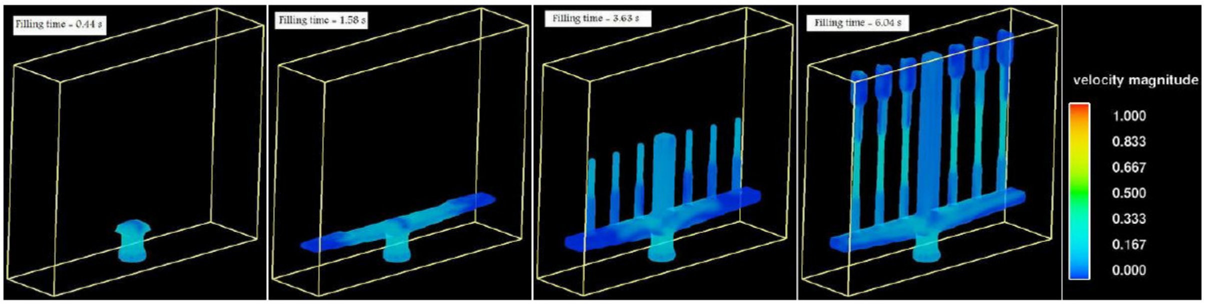


Fig. 5. Comparison of the casting systems of the CRIMSON process (left) and a conventional gravity sand casting (right) to produce a set of tensile bars [27].

Moreover, thanks to Computational Fluid Dynamics (CFD) simulations, it is possible to quantify and observe the advantage of the CRIMSON process in comparison to a conventional pouring method (e.g. gravity sand casting) in terms of metal flow regime while filling the mould (Figure 6).



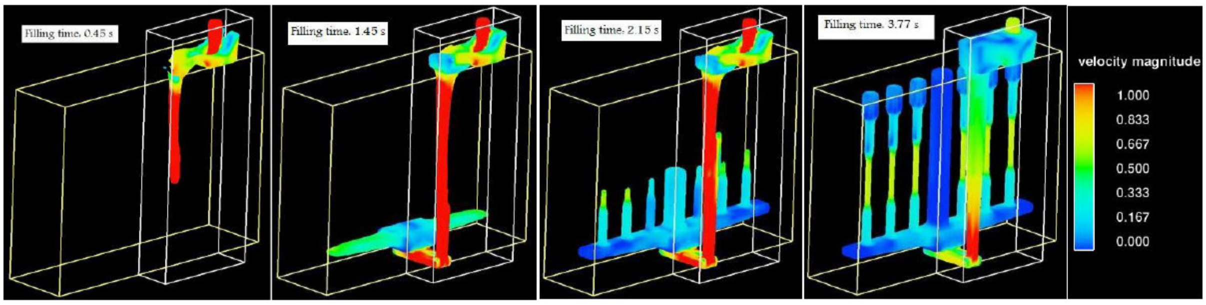


Fig. 6. Comparison of the velocity magnitude at different times of the CRIMSON process (top) and a conventional gravity sand casting (bottom) to produce a set of tensile bars [27].

Volvo Group has developed an energy-efficient, metal casting process tailored to produce automotive cylinder-heads with ferrous alloys. A new foundry was built near Skovde (in Sweden) designed to maximise energy efficiency. ”Foundry G2” has an area of 9600 m^2 with a capacity of 20000 ton/year and 15 operators per shift [40]. The Future Process for Casting (FPC) is the name of the advanced sand casting process, patented by AB Volvo, that uses a combination of chill steel and pressurised water-cooled sand to achieve a quick and controlled cooling of the molten metal. The system keeps the mould stable to avoid defects in the cylinder-heads whereas the pouring system is controlled by fully automated ladles. Volvo claims to increase strength of the product by 10-15% retaining good cast ability and machinability, 85% of the core sand is recycled, approximately 50% energy consumption reduction is obtained recycling the cooling water and the total specific energy consumption slightly above 2 MJ/kg. Such remarkable result in terms of energy efficiency is achieved thanks to a very advanced design where heat recycling does not require any extra equipment to heat the building and the choice of materials does require minimal effort for cleaning [40].

6. “Small is beautiful” approach

“Small is Beautiful” is a new philosophy that intends to tackle the contemporary challenges of the metal casting industry incorporating resource efficiency (both in material and energy terms) and flexible production since the beginning of the design process. In addition to 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 is envisaged.

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. As a result, the need for a structured energy auditing framework and an effective visualisation tool of measurements able to integrate with existing manufacturing systems have been identified [7]. A concise overview of the key aspects comprising “Small is Beautiful” follows. The interested reader is invited to check the cited references to deepen his or her knowledge in this respect.

6.1 Auditing framework

A complete auditing framework of the energy consumption in the plant is essential to drive the optimisation process towards energy efficiency. Usually, conventional manufacturing processes are audited measuring the energy consumption of the machine tools used, that results significantly higher than the theoretical minimum [27]. Ancillary systems could increase considerably further the energy consumption, thus the monitoring procedure should be designed with care because it may not be possible to measure individually or in isolation such additional systems.

To address the mentioned issues, three major phases are designed (Figure 7):

- Preparation: the audit is structured and tailored to the peculiarities of the foundry to be analysed.
- Measurement: after a calibration phase (with no actual casting happening), the measurements are collected
- Analysis: the energy consumption of each phase is calculated and all the other indirect metrics are calculated both at local and system level.

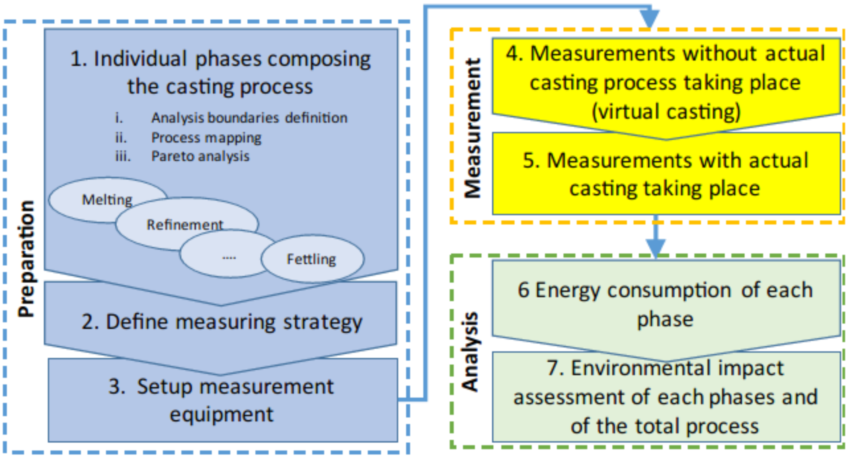


Fig. 7. Energy consumption audit framework [27].

Performing a Pareto analysis of the phases ranked according to the energy consumption (or their associated cost), it is possible to choose the areas with highest return.

The described framework is well-suited for its integration with lean philosophy tools (described in Section 3.2).

6.2 Data visualisation tool

A software to visualise clearly foundry energy and material flows has been developed as a response to an industrial necessity captured within the initial activities of “Small is Beautiful”. The computer program makes possible a clear analysis of the foundry process in its entirety at a flexible level of data granularity. This analysis is intended to help decision makers in considering different scenarios with improvements in various areas and rapidly evaluate their performance with the help of a graphical representation (e.g. using process flow or Sankey diagrams). The analysis aims also at discovering synergistic opportunities hidden in the complete production chain. Furthermore, it is possible to include in the analysis also the supply chain (e.g. mould or die suppliers, inserts manufacturers) and will be able to link to product design software [41, 42].

A general representation of the program work-flow is depicted in Figure 8 and comprises three major steps.

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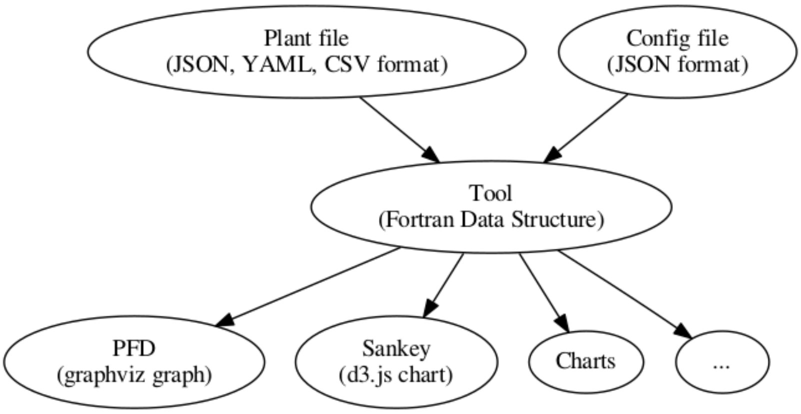

Fig. 8. High-level work-flow of the “Small is Beautiful” data representation tool [42].

In the first instance, two textual input files are necessary to start with the analysis. It is compulsory for the user to prepare a file that describes the metal casting factory (called “Plant file” in Figure 8). Optionally, some configuration features can be specified in the “Config file” and this information will override the default settings.

A minimal excerpt of the previously defined “Plant file” (in YAML format) and of the configuration file are provided in Figures 9 and 10. An additional Graphical User Interface (GUI) to substitute the textual inputs is expected to be included in future releases.

```
...
start component: Melting Furnace
output um_mat_q: kg
output um_en_q: GJ
Components:
  - name: Melting Furnace
    flows:
      - name: Charge
        categ: mat
        dir: in
        qtity: 100
        um_q: kg
      - name: Thermal
        categ: en
        dir: in
        qtity: 20
        um_q: GJ
      - name: Oxidised Metal
        categ: mat
        dir: out
        qtity: 2
        um_q: kg
      - name: Thermal
        categ: en
        dir: out
        qtity: 10
        um_q: GJ
    next comp:
      - name: Holding Furnace
  - name: Holding Furnace
...
```

Fig. 9. Excerpt of the presented tool input file describing the foundry specifications in YAML format [42].

```
{
  "config verbose": false,
  "input file": "input.yaml",
  "categ analysis": "all",
  "graphviz": {
    "comp shape": "box",
    "mat shape": "septagon",
    "en shape": "ellipse",
    "comp foreg colour": "lightblue",
    "mat foreg colour": "yellow",
    "en foreg colour": "red2",
    "show comps lbl": true,
    "show flows lbl": true
  },
  "sankey": {
    "colour path": true,
    "d3 lib path": "rCharts_d3_sankey/libraries/widgets/d3_sankey",
    "d3 templ path from lib": "/layouts/chart.html",
    "width": "960",
    "height": "500"
  }
}
```

Fig. 10. Example of the configuration file used by the tool presented in this work (JSON format) [42].

The second major step of the program work-flow is the generation of an internal data structure. In this phase, the information provided in the “Plant file” is converted into a conveniently flexible format that can be efficiently handled with a programming language.

The internal data structure is used in the third, last step to transform the information about the factory inserted by the user into different graphical outputs. The program is designed modularly to handle a variety of final diagrams and charts and currently it can produce automatically Process Flow Diagrams (PFDs) invoking the graphical library graphviz [43] alongside Sankey diagrams calling a specific plug-in of the javascript library d3.js [44].

Looking at Figure 9, it can be noticed that the required description of the foundry process is basically a list of phases that can be entered in any order but that must specify a connection of one phase with the others. The phases are called “Components” in the “Plant file” and to each of them it can be attached, optionally, a flexible number of input or output energy or material flows.

The implementation of object-oriented features in the program provides some benefits associated with this type of design. For example, the amount of material and energy content processed at each phase is internally calculated applying conservation laws and analysing the input data of the flows with the connection among process phases. Although the calculations to perform at each process phase are different from each category of streams analysed (i.e. material or energy), the algorithm to traverse the entire data structure has been coded only once as a polymorphic object. This design permits to re-use the same algorithm for every type of action (implemented in a procedure) to be performed to the entire data structure representing the foundry [41, 42].

An example of the Sankey diagrams of material and energy flow produced by the program is reported in Figure 11.

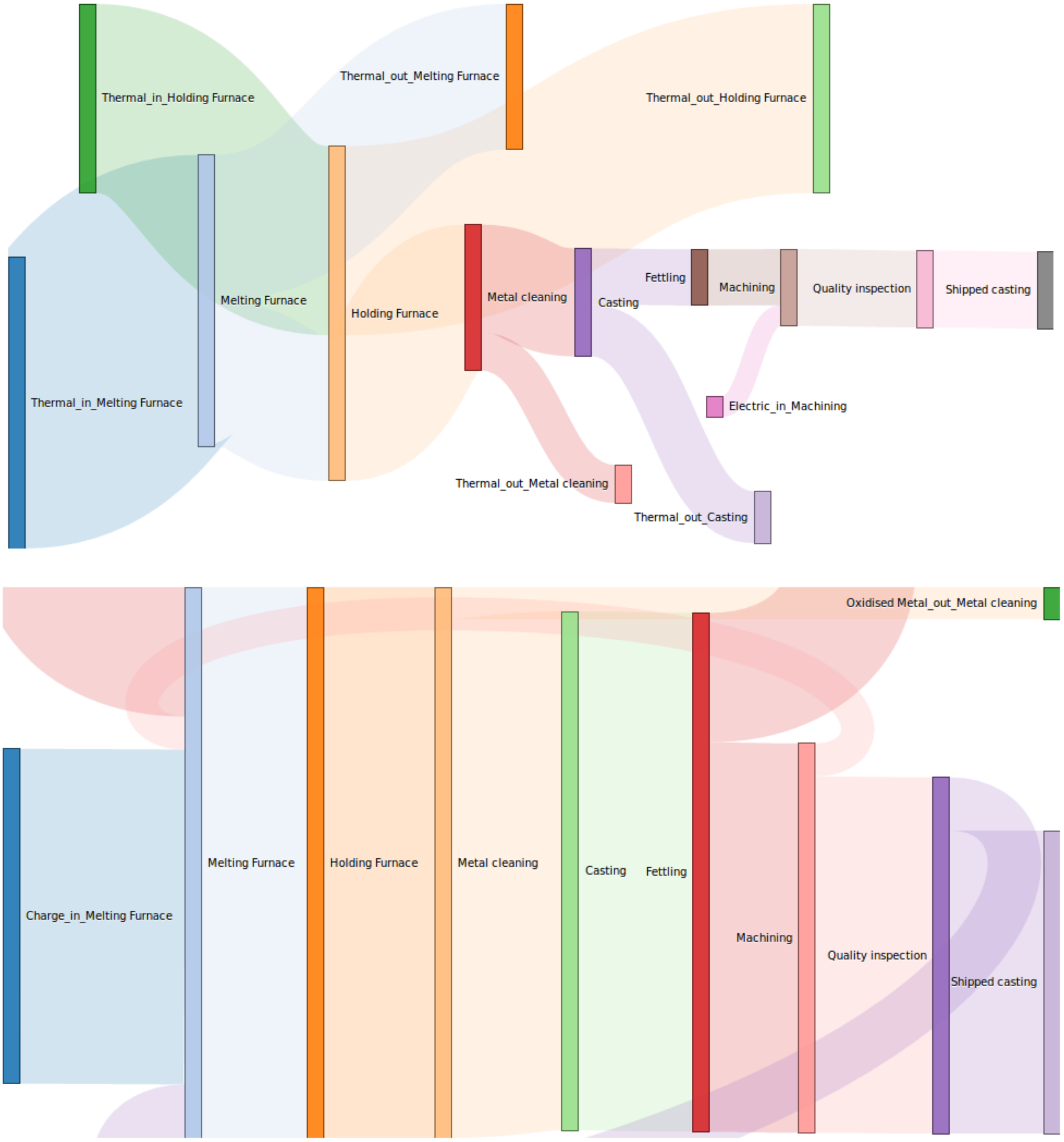

Fig. 11. Example of material (top) and energy (below) flows in Sankey diagrams of a metal casting foundry. The diagrams have been generated by the computer program developed for the "Small is Beautiful" project [42].

Furthermore, the program has been designed to integrate with "legacy" manufacturing systems already established in the industry. When integrated, this tool can perform further tasks alongside energy and material flow analysis. These additional tasks have been categorised according to six scenarios and summarised in Table 2.

Table 2. Scenarios to integrate the tool with existing manufacturing systems [42].

Scenario	Input	Additional benefit
Production improvement	Audited data	Accurate specifications (via interfaced tools, e.g. CFD)
Product design	Manufacturing processes database	Accurate specifications (via interfaced tools, e.g. CFD)
Benchmarking	Reference plants database	Basic Pareto analysis (i.e. find “low-hanging fruits”)
Process monitoring	Real-time data	Process monitoring tool (via Internet of Things)
Training	Real-time data	Personnel didactic tool (via Internet of Things)
Life cycle assessment	Materials life cycle database	Product life cycle analysis

One option would be to interface the program with Computational Fluid Dynamics (CFD) codes for metal casting modelling to add a more detailed layer and analyse specific process phases while investigating alternative design options or improvements to the current product. In this last case, data collected during audits can be used to link the tool to CFD codes whereas a database of manufacturing processes is necessary to serve the same purpose while designing new products. In these scenarios, automatic optimisations can be implemented with profit [42].

Alternatively, the foundry performance can be benchmarked against a database of reference plants, leading to suggestions to improve the aspect that will guarantee the highest return on investment [42].

Another option is monitoring the performance of the foundry using the tool visual capabilities with real-time data. This can be achieved using networking protocols when the equipment in the factory is connected according to a modern, “smart foundry” paradigm. In such scenario, the program can become also a didactic tool to improve the behaviour of the factory personnel that has been often observed to have an important impact on the good performance of manufacturing plants. Furthermore, inverting the direction of the data flow from the program to the production equipment, it is possible to control the process in real-time [42].

Finally, the design of the program permits a relatively simple implementation of embodied energy or CO_2-footprint flows if life cycle databases are made available. This scenario would allow an analysis of the whole life cycle of the foundry products [42].

7. Foundries of the future: a short conclusion

Among the challenges that the foundry industry will have to tackle in the future short-medium term, there is undoubtedly resource scarcity with even tighter environmental regulations. In this context, energy efficient casting studies are of great value and interest to preserve competitiveness and environmental protection. Both managerial and technical improvements can contribute to enhancements towards this goals although so far they have been considered with different priorities. The foundries of the future will have to consider as an important activity to control their processes, a thorough analysis of material and energy flows together with a culture inspired by the lean manufacturing paradigm. These main aspects have been described in this work showing examples of energy efficient casting implementations. In particular, as a philosophy well-aligned along the mentioned goals, "Small is Beautiful" have been presented. A potential extension of its current framework to encompass the entire sustainability spectrum appears feasible in the near future.

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References

[1] M.R. Jolly, Castings, in: I. Milne, R.O. Ritchie, B. Karihaloo (Eds.), Comprehensive Structural Integrity, first ed., Elsevier, Oxford, 2003, pp. 377–466.
[2] J. Elkington, Cannibals with Forks: the Triple Bottom Line of 21st Century Business, Capstone, 1997.
[3] UKcastings.org, http://ukcastings.org/page.asp?node=79&sec=Facts___Figures (accessed on 7th August 2017).
[4] The European Foundry Association, http://www.caef.org/downloads/kategorie.asp?kat=9 (accessed on 7th August 2017).
[5] The World Bank Group, http://data.worldbank.org/indicator/SP.POP.TOTL?end=2015&start=1960&year_high_desc=true (accessed on 7th August 2017).
[6] The World Foundry Organisation, http://www.thewfo.com/contentfiles/downloads/35.pdf (accessed on 7th August 2017).
[7] M.R. Jolly, K. Salonitis, F. Charnley, P. Ball, H. Mehrabi, E. Pagone, Energy Efficiency Status-Quo at UK Foundries: The "Small-Is-Beautiful" Project, in: A.P. Ratvik (Eds.), Light Metals 2017, Springer, Cham, 2017, pp. 917–923.

[8] E.P. DeGarmo, J.T. Black, R.A. Kohser, Materials and Processes in Manufacturing, 9th ed., New York, Wiley, 2003.

[9] American Society for Metals, ASM Handbook, 1st ed., Ohio, ASM International, 1980.

[10] J.F. Schifo, J.T. Radia, Theoretical/best practice energy use in metalcasting operations. USA Department of Energy, Energy Efficiency and Renewable Energy, 2004.

[11] R.M. Torielli, R.A. Abrahams, R.W. Smillie, R.C. Voigt, Using lean methodologies for economically and environmentally sustainable foundries, The 69th World Foundry Congress, 2011.

[12] J.R. Duflou, J.W. Sutherland, S. Dornfield, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, K. Kellens, Towards energy and resource efficient manufacturing: a processes and systems approach, CIRP Annals – Manufacturing Technology, vol. 61(2), pp. 587-609, 2012.

[13] J.C. Brunke, M. Johansson, P. Thollander, Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry, Journal of Cleaner Production, vol. 84(1), pp. 509-525, 2014.

[14] E. Cagno, P. Trucco, A. Trianni, G. Sala, Quick-E-scan: A methodology for the energy scan of SMEs, Energy, vol. 35(5), pp. 1916-1926, 2010.

[15] A. Sa, S. Paramonova, P. Thollander, E. Cagno, Classification of Industrial Energy Management Practices – A case study of a Swedish foundry, Energy Procedia, vol. 75, pp. 2581-2588, 2015.

[16] P. Thollander, M. Ottosson, Energy management practices in Swedish energy-intensive industries, Journal of Cleaner Production, vol. 18(12), pp. 1125-1133, 2010.

[17] J.P. Womack, The machine that changed the world: based on the Massachusetts Institute of Technology 5-million dollar 5-year study on the future of the automobile, New York, Rawson Associates, 1990.

[18] C. Herrmann, S. Thiede, J. Stehr, L. Bergmann, An environmental perspective on Lean Production, Manufacturing Systems and Technologies for the New Frontier: The 41st CIRP Conference on Manufacturing Systems, vol. 83, 2008

[19] Lean Manufacturing and the Environment: Research on Advanced Manufacturing Systems and the Environment and Recommendations for Leveraging Better Environmental Performance, USA Environmental Protection Agency, 2007.

[20] F.A. Abdulmalek, J. Rajgopal, Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study, International Journal of Production Economics, vol. 107(1), pp. 223-236, 2007.

[21] Besta, P., Stoch, M. and Haverland, J. (2011), Lean manufacturing concept in metallurgical industry, Metal 2011

[22] Shingo Prize for Operational Excellence, Application Guidelines, Logan, Utah State University Jon M Huntsman School of Business, 2010.

[23] S. Rothenberg, F. Pil, J. Maxwell, Lean, green, and the quest for superior environmental performance, Production and Operations Management, vol. 10, pp. 228-243, 2001.

[24] C Yang, S Lin, Y Chan, C Sheu, Mediated effect of environmental management on manufacturing competitiveness: An empirical study, International Journal of Production Economics, vol. 123, pp. 210-220, 2010.
[25] A.A. King, M.J. Lenox, Lean and Green? An empirical examination of the relationship between lean production and environmental performance, Production and Operations Management, vol. 10, pp. 244-256, 2001.
[26] ISO Energy Management System, ISO standard 50001, International Organization for Standardization, Geneva, Switzerland, 2011.
[27] K. Salonitis, M.R. Jolly, B. Zeng, H. Mehrabi, Improvements in energy consumption and environmental impact by novel single shot melting process for casting, Journal of Cleaner Production, vol. 137, pp. 1532-1542, 2016.
[28] N.M. Gandhi, V. Selladurai, P. Santhi, Green productivity indexing: A practical step towards integrating environmental protection into corporate performance, International Journal of Productivity and Performance Management, vol. 55, pp. 594-606, 2006.
[29] S.L. Nimbulkar, R.S. Dalu, Design optimization of gating and feeding system through simulation technique for sand casting of wear plate, Perspectives in Science, vol. 8, pp. 39-42, 2016.
[30] P.R. McCright, G.G. Bergmiller, Techniques for Enhancing Sustainability of Industrial Operations, IEEE Green Technology Conference, Lubbox, USA, 2010.
[31] C.S. de Oliveira, E.B. Pinto, Lean manufacturing paradigm in the foundry industry, Estudos Tecnologicos em Engenharia, vol. 4(3), pp.218-230, 2008.
[32] G. Hari Priya, H. Ramakrishna, Y. Sundara Rajalu, Sand Casting Process Improvement Using Lean Principles, International Journal of Research in Engineering and Technology, vol. 4(14), pp. 97-106, 2015.
[33] M. Suarez, J.A. Davila, F. Vasquez, Supply Chain Value Stream Mapping: a new tool of operation management, International Journal of Quality & Reliability Management, vol. 33(4), pp. 518-534, 2006.
[34] M. Lazzarin, R.M. Noro, Energy audit experiences in foundries, International Journal of Energy and Environmental Engineering, vol. 7(4), pp. 409-423, 2016.
[35] M. Arasu, R.L. Jeffrey, Energy Consumption Studies in Cast Iron Foundries, Transaction of 57th IFC, 2009.
[36] O. Yilmaz, A. Anctil, T. Karanfil, LCA as a decision support tool for evaluation of best available techniques (BATs) for cleaner production of iron casting, Journal of Cleaner Production, vol. 105, pp. 337-347, 2015.
[37] Z. Shan, S. Qin, Q. Liu, F. Liu, Key Manufacturing Technology & Equipment for Energy Saving and Emissions Reduction in Mechanical Equipment Industry, International Journal of Precision Engineering and Manufacturing, vol. 13(7), pp. 1095-1100, 2012.
[38] G. Gigante, How can we become a practical green foundry industry?, International Journal of Metal Casting, vol. 4(3), pp. 7-15, 2010.
[39] X. Dai, M.R. Jolly, B. Zeng, The capability enhancement of aluminium casting process by application of the novel CRIMSON method, Shape casting: 4th international symposium, pp. 265-272, 2011.

[40] Volvo – A foundry with a vision, http://www.gjuterihandboken.se/media/35214/det_rena_gjuteriet.pdf (accessed on 7th August 2017).

[41] E. Pagone, M.R. Jolly, K. Salonitis, The development of a tool to promote sustainability in casting processes. Procedia CIRP 55, pp. 53-58, 2016.

[42] E. Pagone, M.R. Jolly, K. Salonitis, A tool to promote sustainability in casting processes: development highlights, in: G. Campana, R.J. Howlett, R. Setchi, B. Cimatti (Eds.), Selected papers on Sustainable Design and Manufacturing, Springer, Cham, 2017, pp. 172-184.

[43] E.R. Gansner, S.C. North, An open graph visualization system and its applications to software engineering, Software – Practice and Experience, vol. 30(11), pp. 1203–1233, 2000.

[44] M. Bostock, V. Ogievetsky, J. Heer, D3: Data-driven documents. IEEE Trans Visualization & Comp Graphics (Proc InfoVis), 2011.

Energy-efficient casting processes

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