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The development of a tool to promote sustainability in casting processes

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Abstract

The drive of the manufacturing industry towards productivity, quality and profitability has been supported in the last century by the availability of relatively cheap and abundant energy sources with limited focus on the minimisation of energy and material waste. However, in the last decades, more and more stringent regulations aimed at reducing pollution and consumption of resources have been introduced worldwide and in particular in Europe. Consequently, a highly mature and competitive industry like foundry is expecting challenges that an endeavour towards sustainability can turn into significant opportunities for the future. A tool to undertake a systematic analysis of energy and material flows in the casting process is being developed. An overview of the computer program architecture is presented and its output has been validated against real-world data collected from foundries.

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Keywords: Energy efficiency; Sustainable development; Casting

1. Introduction

Metal casting is an energy intensive, technically challenging, manufacturing process with a long history that plays a vital role in the production of a large variety of products. In very simple terms, casting can be summarised by the following description. Melt metal is poured into a mould that has been shaped as required and then removed after solidification. Casting is usually competitive over other manufacturing processes when it is necessary to produce parts with complex geometries or when dealing with materials difficult to machine [1,2].

In the last years, two significant forces are imposing a change to the mature technology of the metal casting industry. On the one hand, there is broad consensus within the society about the necessity to minimise waste and pollution derived by anthropogenic activities. This urge reflects in the more and more stringent regulations at national and European level as well as in worldwide agreements like the one settled in December 2015 at the UN Climate Change Conference.

On the other hand, the increasingly aggressive competition deriving from the modern global economy pushes towards a more energy effective use at a reasonable cost. Sustainability appears as an appealing strategy to tackle these challenges bringing together additional benefits. According to its most famous definition (given by the Brundtland Commission of the United Nations in 1987), “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [3]. Given its extensive impact on modern society, manufacturing (and, in turn, casting) is required to play an important role in this context, evolving swiftly to cope with the changes, if not anticipating them. For example, Salonitis and Stavropoulos [4] propose to improve the established approach based on the “manufacturing decision tetrahedron” comprising cost, quality, flexibility and time adding sustainability as an additional fundamental driver of modern manufacturing.

In practice, a sustainable approach requires a broad and comprehensive view that covers the entire life-cycle of a product during its design and aims at maximising environmental, economic and social Key Performance Indicators (KPIs). The tool presented in this work assists foundries in this direction with an initial focus on the environmental aspects without encompassing the whole supply chain or “end of life” aspects.

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2. Rationale

Among the key findings of a workshop attended by foundries, suppliers and consultants, it has been highlighted the need for an energy auditing framework and a tool for the fast analysis of measurements [5-7]. The software under development is designed to respond to this industry need supporting a systematic analysis of the full energy and material chain of casting processes from charge materials through to waste. The visualisation of flows in different forms (e.g. process flow or Sankey diagrams) can support decision making in exploring the impact of potential improvements. For example, waste that can be considered non-trivial or traditionally unaccounted can be identified alongside opportunities for scavenging and the associated cost. Moreover, the visual nature of the computer program output can be effectively implemented in the training of foundry personnel whose behaviour plays a vital role in implementing sustainable improvements. Finally, this thorough analysis can be used for benchmarking performance of the plant against similar ones.

Although some of the mentioned goals might be obtained using established Discrete-Event Simulation (DES) tools, the time, effort or skills required to set-up a realistic model of the plant can be unacceptable for many SMEs. Hence, the program presented in this work has been designed to require minimum effort to map out the required flows and the amount of information corresponding to the desired level of accuracy can be flexibly adapted to the user's needs.

3. Energy flows

The cost of energy affects significantly the competitiveness of energy intensive enterprises like foundries. Thus, there is an interest in pursuing measures aimed at reducing the consumption of fossil fuel and electric power. Options to identify opportunities to reduce energy consumption include audits and the application of "lean philosophy" [8].

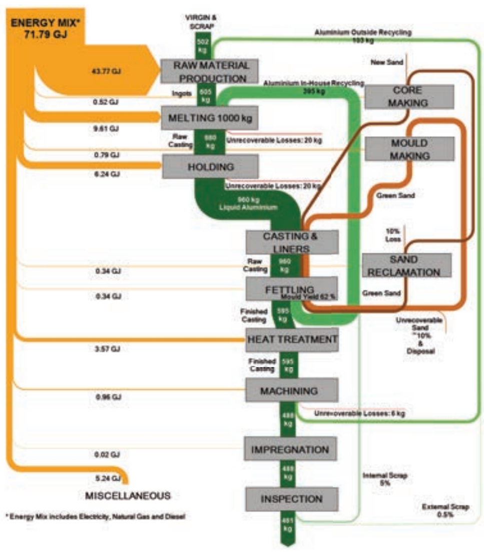

Fig. 1. Example of material and energy flows in a foundry represented by a Sankey diagram.

Suggestions derived by energy audits generally focus on equipment updates that would guarantee the maximum return on the investment [9,10]. However, the relevant capitals required could prevent the adoption of the most beneficial measures from an energy saving point of view. In fact, SMEs (that represent a major fraction of foundries) seek relatively short payback times [11-13].

Alternatively, the adoption of one or more lean philosophy tools may allow energy savings avoiding the larger investments in equipment previously mentioned. Salonitis *et al.* review more in detail the available options also remarking that lean tools are generally less implemented in firms where large stocks of raw materials are present, like foundries [8].

4. Material flows

Material flows represent another important source of information to improve casting processes. A schematic example in the form of a Sankey diagram of material and energy flows within a foundry is shown in Figure 1.

Unrecoverable material losses like (for example) hot flue gas derived from the combustion of fossil fuels, deteriorated scrap metal or sand that cannot be re-melt or reclaimed, are mainly a source of pollution for the environment. Furthermore, waste also "contain" a certain amount of energy that was previously spent in the foundry for its production, even without considering a more comprehensive and complicated life cycle analysis that would extend along the whole supply chain.

More virtuous examples like re-melting scrap metal after fettling (i.e. the operation that separates the casting from its gating system) where there is no transfer of metal outside the boundaries of the plant, still contribute significantly to reduce the efficiency of a foundry. Thus, any action focussed on the limitation of any form of waste is useful to improve the process. For example, a reduction of the scrap metal internally re-melt determines an inherent reduction in the energy consumption for unit of shipped casting. Salonitis *et al.* revise a number of opportunities to improve the energy efficiency of a foundry through the indirect means of controlling material flows [8].

An effective metric that can be adopted to describe the overall material efficiency of a foundry in terms of cast metal is the Operational Material Efficiency (OME) expressed as the ratio between the amount of shipped casting over the amount of metal melt measured over a given amount of time [14].

5. Methods

The computer program presented in this work is written in modern Fortran language. Its work-flow starts from a textual input file containing a description of the plant. This information is parsed, categorised and stored into an internal, suitable data structure that is the key component of the tool allowing a flexible conversion of its content according to the final representation required. A modular architecture interfaces the tool with other packages for the final graphical representation of the information (Figure 2).

Currently, the tool interfaces with the open source graph visualisation software graphviz [15] to draw Process Flow Diagrams (PFDs). This feature will be used for the validation presented in Section 7. Work is undergoing to create an interface to the open source statistical software environment and programming language R [16]. The main motivation to develop an interface to the R language is to create automatically Sankey diagrams similar to the example reported in Figure 1. A more detailed description of the relevant process is presented in Section 5.4. Furthermore, it would be possible to develop additional modules to generate other types of chart.

5.1. Input file

The input file is expected to be text based and prepared in JSON format. According to its standard, "*JSON is a lightweight, text-based, language-independent data interchange format*" [17]. JSON has been chosen for its simple structure, the relative abundant availability of parsing libraries and its ability to easily interface with other pieces of software. Regarding the latter point, it may be relatively simple, for example, to write in the future a Graphical User Interface (GUI) program that collects the information about the plant in a more user friendly way. In this case, the JSON input file would be the data interchange element between the GUI and the tool presented in this paper. The parser of the tool uses the open source JSON-Fortran library [18].

5.2. Data structure

After parsing, a description of the entire plant is stored internally for further post-processing in a nested, Fortran-language derived data type and its implementation follows an object-oriented design. The overall plant data structure contains a number of interconnected "components" each of them, in turn, comprise a variable number of flows. Each flow is characterised by the direction (inwards and outwards with respect to the relevant component) and by its category. Two flow categories are currently implemented: material and energy. However, the plant derived data type can be easily extended for future enhancement of the capabilities. A minimal example of the JSON input file structure follows.

```
{
  "Components": [
    {
      "name": “Raw material",
      "flows": [
        {
          "name": “Virgin metal",
          "categ": "mat",
          "dir": "in",
          "qtity": 502,
           "um_q": “kg",
           }
         ],
       “next comp”: [
           “Melting”
           ]
       },
   ...
     ],
     “plant name”: “Sand casting plant”,
     “start component”: “Raw material”,
   ...
   }
```

The traverse routine is a polymorphic object that allows to call the same traversing algorithm from every post-processing module implemented, interfacing correctly with the plant derived data type.

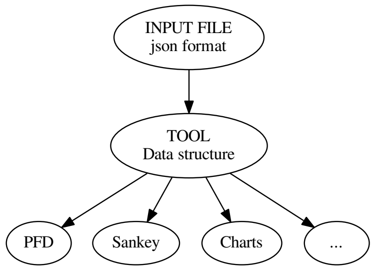

Fig. 2. Work-flow of the proposed data visualisation tool.

5.3. PFD module

The PFD module interfaces with graphviz creating automatically a graph with a user-specified set of colours and shapes to represent components and flows according to the description provided in the previous section. It is possible to selectively filter certain types of flows to represent or, if all flows are requested, it is possible to hide some flows that describe the same physical process in two different categories. For example, in a furnace fossil fuels and air (materials) describe the same physical process of thermal energy input and should not be represented at the same time. Hence, besides a default behaviour, it is possible to specify for every case when such condition arises, what category of the flow will be represented in the PFD.

5.4. Sankey diagram module

Work is underway to generate automatically a Sankey diagram interfacing the tool to the JavaScript library d3.js [19,20]. The integration is indirect by means of an R script (created and run automatically) that invokes the network analysis package igraph [21]. Finally, igraph executes the d3.js library routines for the final rendering. The entire process is designed to be totally transparent to the final user that will only see the data contained in the input file converted into a Sankey diagram.

5.5. Additional charts

Traditional (e.g. pie or histogram) charts can be concurrently generated to complete a techno-economic analysis of the plant extracting the relevant information from the data structure. The development of this module is planned for future work.

5.6. Implementation

Figure 3 shows a simplified UML class diagram that includes more detail about the main derived data types, their methods and inter-connections. A comprehensive analysis of the diagram would go beyond the scope of this work but a concise description is provided. The derived data type methods have mostly self-explanatory names and follow the classic object-oriented naming convention of "get", "set" and "predicate" procedures [22].

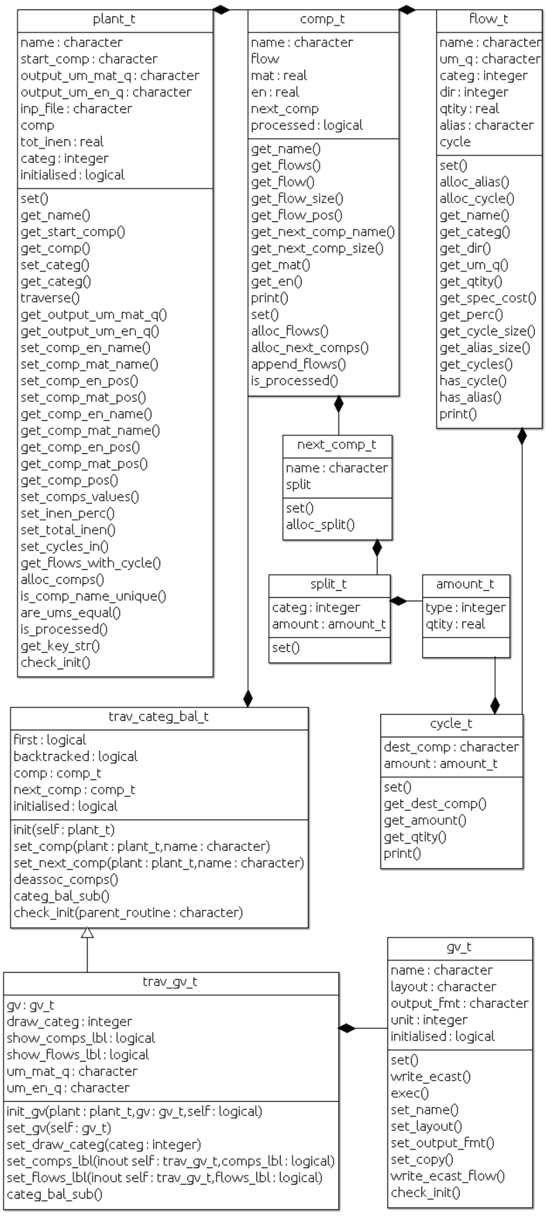

Fig. 3. Simplified UML class diagram of the software under development showing the derived data types, their methods and inter-connections.

The entire plant data type `plant_t`, alongside basic variables like its name, the name of the component to start the analysis (`start_comp`), the name of the input file (`inp_file`), the expected output unit of measure for material and energy flows (`output_um_mat_q` and `output_um_en_q`), an initialisation flag (`initialised`), integrates a number of components `comp` of the type `comp_t`. The program computes and stores internally (still as elements of the `plant_t` type) also the value of the total energy input (`tot_inen` variable) – an important quantity for the purpose of the software – and the category of the flows that has been selected for the analysis (`categ`) – that currently can be set to material (`mat`), energy (`en`) or their combination (`all`).

Each component of the plant (`comp_t` type) is connected to the next component(s) by a specific derived data type `next_comp_t` and contains a number of flows (`flow_t` type), together with its name, its amount of material and energy included (`mat` and `en`) and a `processed` flag.

The `next_comp_t` data type includes the name(s) of the next component(s) and a `split_t` data structure necessary in case of multiple paths ahead, to describe how the amount contained in the current component for each category will be distributed to the successor components. Type `split_t` includes the `amount_t` data type to set if the amount to be split among the next components will be based on the absolute or relative terms of the current component content.

The flow data structure contained in every variable of type `comp_t` is of type `flow_t`. The latter comprises a name, a unit of measure (`um_q`), a category and direction specifier (`categ` and `dir`), its amount (`qtity`) and the optional `alias` element necessary to indicate that the current flow represents the same physical process of other flows (as described in Section 5.3). The implementation details about the logic on how to handle "aliased" flows would go beyond the scope of the current article. Finally, the data type `flow_t` encapsulates the element cycle (of type `cycle_t`) to model flows re-cycled back (e.g. re-melting of scrap metal after fettling). Also type `cycle_t` encapsulate the data structure `amount_t` because the part of the flow to be re-cycled can be set as an absolute or relative quantity.

The traversing routine of the plant (a method of the `plant_t` type called `traverse`), as anticipated, uses polymorphic instances of the basic type `trav_categ_bal_t` that contains all the elements to explore automatically the entire plant structure to ensure that basic conservation laws for each category (i.e. material and energy) are respected while processing each plant component. The type `trav_categ_bal_t` is then inherited by the type `trav_gv_t` that includes some more elements to create the PFD while invoking the `traverse` method. The type `trav_gv_t` encapsulates type `gv_t` that is used to instantiate graphviz graphs objects.

6. Potential applications

Besides the standalone use of the software, several "scenarios" have been envisaged for its integration with existing manufacturing systems that can provide extra benefits beyond the visual representation of the flows in the foundry.

Table 1 shows a summary and comparison of the options. Interfacing the program with specialised tools to design or simulate accurately some specific process steps (e.g. Computational Fluid Dynamics codes for the casting phase) it would be possible to explore in detail improvements of the production line or design a new one. In this context, automatic optimisation capabilities may be implemented too. Moreover, using a database of reference foundries, a benchmarking exercise would identify the highest return on investment improvements available after a basic Pareto analysis. Other opportunities arise when production line, real-time data are available to the software allowing the implementation of process monitoring measures or the training of foundry personnel to behave correctly in the most energy intensive phases (or a combination of them). Finally, using a database of embodied energy of the materials involved, it would be possible to conduct a full life cycle analysis of the product.

Table 1. Main features of the scenarios for the integration of the tool with legacy systems.

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
Training	Real-time data	Personnel didactic tool
Life cycle assessment	Materials life cycle database	Product life cycle analysis

7. Validation

A validation based on the PFD representation of data collected from real foundries is presented (Figure 4). The plant produces aluminium alloy, passenger vehicle automotive parts with a low pressure, sand casting process. Material and energy data are normalised for melting 1000 kg of aluminium alloy and no distinction between thermal and electric energy is provided. Plant components representing a certain stage of the process are drawn as rectangular, light-blue items, whereas material flows are yellow septagons and, finally, energy flows are red and elliptically shaped.

Before melting, virgin metal is mixed with “external scrap”, i.e. metal provided by an external contractor that returns a quantity of raw material equal to the amount received at later stages in the process. This is indicated in the PFD with the “external scrap” outbound flows of the “machining” and “inspection” phases linked (for the sake of simplicity) directly to the “raw material production” stage. During the melting phase also in-house recycled material (i.e. “internal scrap”) from the “fettling” and “inspection” phases is added and, at the same time, an unrecoverable metal loss is generated mostly because of oxidation. Melting requires almost 44% of the entire process energy input.

The following holding phase, that takes place in a different furnace, is necessary for two main reasons. Firstly, it acts as a buffer to accommodate different production rates and also allows the refinement of the molten aluminium alloy making the metal oxides float to the surface. In this way, it is easy to subsequently remove the so-called “dross”, that is another source of unrecoverable material loss. Also the holding phase represents a significant fraction of the energy input of the entire process (about 28%).

Core and mould making is a closed-loop subsystem connected to the metal processing and it is visible in the bottom left part of the chart of Figure 4. The sand mould has the

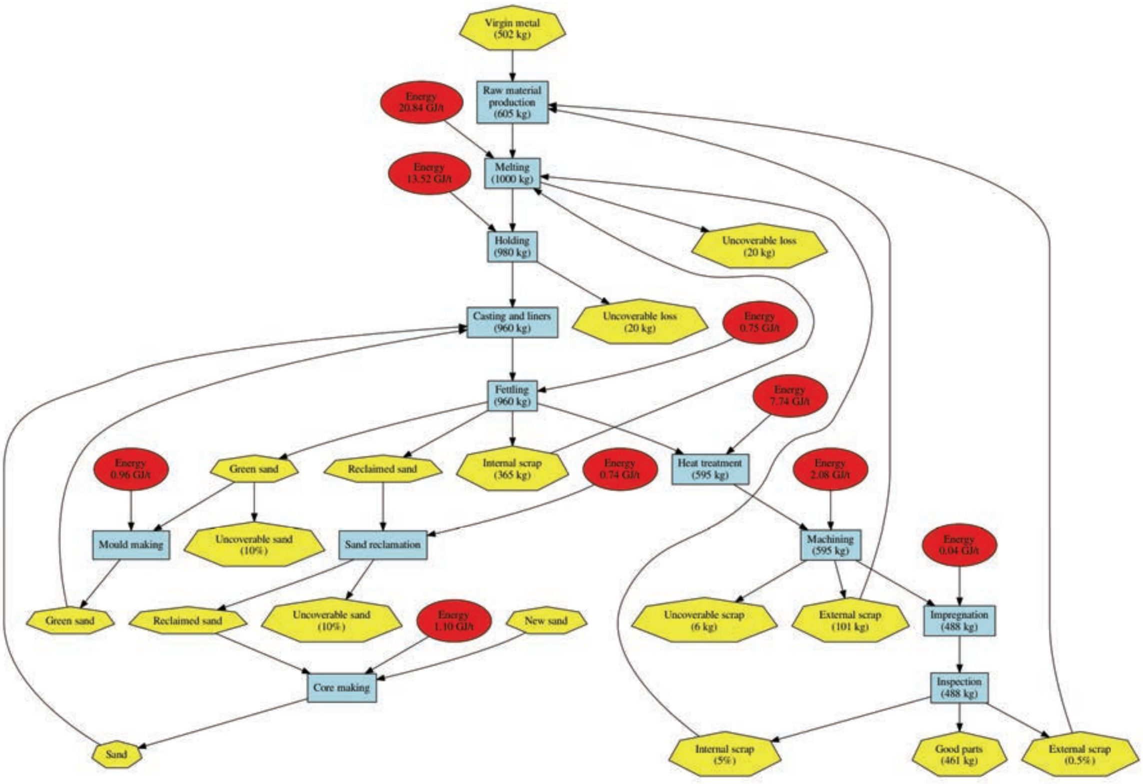

Fig. 4: Example showing the overall material and energy flows in a foundry melting Aluminium alloys with a low pressure sand casting process.

purpose to form the outer limits of the casting and support the core package. The core is generated by a cold box method where a binder system “cures” the silica sand and resin. The entire mould and core making requires roughly 6% of the total energy input.

The casting phase is the most characteristic step of the entire process where the molten metal fills the prepared mould and solidifies. Subsequently, the mould is removed, the core sand shaken out and the gating and runners are removed in the fettling phase. As previously mentioned, the metal removed is internally recycled into the melting furnace. Although not large, the input energy spent in this phase is not negligible (about 1.6% of the total).

A heat treatment is then necessary to improve fatigue and wear properties of engine blocks, requiring a substantial amount of input energy, i.e. 16% of the total.

Many surfaces are cast with 2-3 mm of excess material that is removed in a machining step to attain the dimensional accuracy and surface finish according to the design specifications. Several operations generate a part of recyclable scrap that is processed by an external enterprise (i.e. “external scrap” described above) alongside a smaller part of unrecoverable, deteriorated metal. Machining accounts for about 4.4% of the total energy input.

The next phase is impregnation: the introduction of a polymer sealant in the pores and cracks generated in the castings by the imperfect solidification of the liquid metal. Main causes of porosities are turbulence in the metal flow, gas entrapment and uneven metal shrinkage that are promoted especially in aluminium alloys by its significant volumetric shrinkage and hydrogen content. Impregnation is necessary to guarantee the necessary sealing capabilities of the parts that will withstand high pressure. The vacuum dry process adopted for this phase in the plant considered requires a modest 0.1% of the total energy input.

A final inspection separates the good blocks to be shipped from the others that could be internally or externally recycled according to the mentioned procedures. It should be noted that although the representation of the process shown is already quite accurate, it could be progressively improved with more details if the information is available (e.g. a distinction between thermal and electric energy, an estimate of the outgoing thermal flows, etc.) simply editing the input file.

8. Conclusion

A computer program to assist foundries in the transition to a more sustainable way of production is presented at the current state of development and validated against real world data. Through the graphical representation of processes, it is possible to clearly identify the main areas of intervention that can be intended in terms of technical solutions on the foundry equipment as well as a didactic tool for the education of the personnel aiming to improve their behaviour.

The program has been designed for maximum flexibility and with a modular architecture, thus it can be integrated with a GUI with limited effort. The implementation of an economic analysis module is under consideration to provide a more thorough analysis. Similarly, life-cycle analysis capabilities are of interest and can be implemented, for example, in the form of embedded energy flows. Finally, the integration with Computational Fluid Dynamics established codes for casting application can be of interest.

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