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Energy resilient foundries: The "Small is beautiful" projects

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Abstract:

Applying the concept of "small is beautiful" into a conservative relatively low technology manufacturing sector where the "economies of scale" argument has been used to build ever more so-called efficient process lines is a major challenge. The energy efficiency of the casting process has only been investigated in a limited fashion. The two “Small is Beautiful” projects aimed to introduce a new concept into foundries with regards the use of their resources. The new philosophy, "small is beautiful", starts by encouraging the use of high-quality feedstock, only melting what is required and only when it is required. Recycling of internal scrap is not necessarily acceptable but an aim for higher yields is. Applying counter gravity casting methods to improve yield and give enhanced quality is encouraged as is the recovery of low-grade heat from solidification. The present paper discusses the research undertaken and the key findings from the two projects.

Keywords: Sustainability; Aluminum; Modelling and Simulation

1. Introduction

It has been widely stated that the manufacturing sector accounts for more than 35% of the total energy consumption and the associated emissions. Within of course the manufacturing sector, a wide breadth of manufacturing systems, technologies and processes are employed, with some of them being more or less energy “hungry” than others. The foundry sector is clearly among the most energy intensive sectors and potentially a sector where great impact can be achieved. Putting that in the context of the United Kingdom, foundry sector is composed of more than 400 organizations, most of them being small and medium enterprises [1], with a total value of products that exceeds £2.5B. Foundries can be considered as traditional organizations both in terms of the technologies used as well as with regards the culture within them. The focus has been for very long on making things “faster, cheaper and better”, and not necessarily in a energy and resource in general resilient way. The U.K. government identified the importance of these issues and is supporting industry through a number of initiatives. Academia is commissioned to undertake research for helping manufacturing sector transform and meet the net zero 2050 agenda.

The Engineering and Physical Sciences Research Council (EPSRC), who is the UK’s main agency for funding research in engineering and the physical sciences, funded two research grants to Cranfield University for addressing this research gap. The first project, that served as a feasibility study, under the title “Small is Beautiful” was launched on March 2015 end ended in December 2016. The principal objective of the study was to “develop a new philosophy/methodology and a software tool incorporating metrics for the handling of materials and energy throughout the process in foundries using computer numerical process simulation to support the decision making”. The key findings of the project were presented at the TMS 2017 Conference [2]. The project was successful, and a follow up, large scale project was commissioned to Cranfield University that started on January 2017 and was completed in January 2021. The main aim of the second phase was the establishment of a toolbox that can be used by foundries for improving their resource efficiency. In the present paper, the results of both the “Small is Beautiful” projects will be presented, focusing mostly on the second phase of the project, and presenting for the first time the toolbox as whole.

2. The “Small is Beautiful” philosophy

The “Small is Beautiful” (SiB) concept is a new philosophy to challenge the conventional “economies of scale” thinking which is prevalent in manufacturing and the casting industry specifically. As well enabling energy reduction and resilience the philosophy enables the move to more flexible production. Small is Beautiful focused on delivering a set of methodologies, metrics and tools for the design of agile manufacturing processes for the casting sector, that are efficient in terms of energy and materials usage but at the same time are profitable and responsive to market needs. The SiB toolbox will guide engineers and production planners to determine processing routes that lead to the least energy and material usage at the right yield, yet accurately responding to customer demands. Throughout the project’s duration research on specific methods and tools was undertaken for supporting this new philosophy.

The SiB philosophy encourages the use of high-quality feedstock, only melting what is required and crucially only when it is required. This is materialized to a great degree in the casting method developed initially at Birmingham University and then at Cranfield University, so called CRIMSON (Constrained Rapid Induction Melting Single Shot Up-casting) process. The process uses a rapid induction furnace to melt just enough metal for one single casting; then transfer the molten charge to a computer controlled counter gravity casting platform. The highly controlled metal flow is pushed into the mould to finish the pouring and solidification. Such process reduces the defect generation and energy consumption by rapid melting, minimum holding and smooth filling of the mould.

3. Key elements of the toolbox

3.1 Easy wins – the lean approach

Lean manufacturing comes with a set of proven tools that can help improve the efficiency of any manufacturing system. Instead of direct energy saving through capital investments in new assets, lean philosophy can be introduced to eliminate waste, improve quality and eventually, achieve the goal of energy saving. Salonitis et al. [3] reviewed the various lean tools and techniques and their applicability to foundries. Techniques such as Single Minute Exchange of Dies (SMED), 5S, Value Stream Mapping (VSM) and visual management can be applied in straightforwardly in any foundry. Other techniques such as Just in time and production levelling might be less applicable.

4.2 Metrics and Energy auditing framework

The SiB feasibility study [2] highlighted that foundries do not monitor the energy consumption in detail, but rather focus in energy bills. This was mostly attributed to lack of know-how on measuring with the appropriate resolution and granularity, as well as the limited availability of tailored to foundries metrics. In the context of SiB project, Pagone et al. [4]

proposed a set of metrics focused on the energy and material efficiency. Further to the widely used Specific Energy Consumption (SEC), that is defined as the total energy consumption over a unit of time divided by either the total amount of good castings shipped (SEC_o) or the total amount of material melted (SEC_m), three main new metrics were also introduced. Namely, the non-dimensional overall process efficiency (η_o), the fraction of total energy input per asset (φ) and the Operational Material Efficiency (OME). The new metrics were compared with the traditional ones for the use with five different sand-casting processes (fig. 1). The new metrics improved traditional parameters to represent a clear benchmarking tool against the theoretical minimum energy required by the overall process, according to a clear, non-dimensional scale bounded between 0 and 1. The new set of metrics has been proven particularly useful comparing real-world data related to a product manufactured from different alloys (i.e. Aluminium, Magnesium and Zinc-based alloys) using the same High-Pressure Die Casting (HPDC) process [5]. In this case, SEC_o showed very similar values for the Aluminium and Zinc alloy foundries, whereas η_o (that takes into account the thermodynamic characteristic of the specific alloy) uncovered the potential to improve further the Zinc-based process, and φ identified in the melting and holding phases the opportunity for improvement [6].

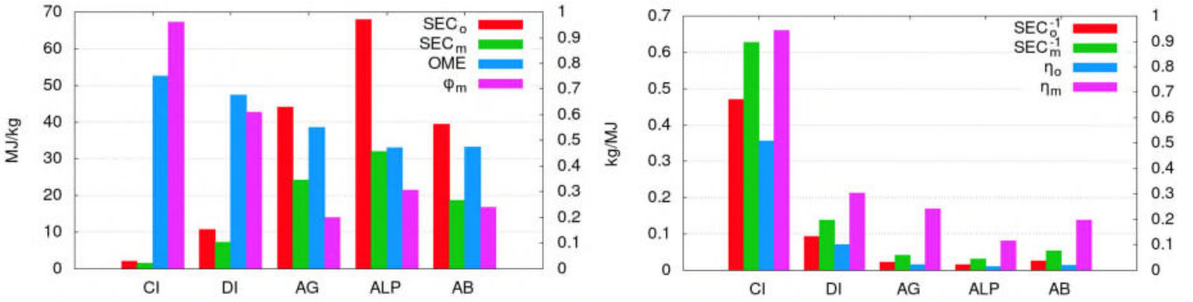


Figure 1: Comparison of different metrics for assessing the casting processes performance [4]

The feasibility phase also identified the lack of a structured approach for measuring the resource consumptions and presenting the results. In order to bridge this gap, an energy audit framework was developed and validated [7]. Figure 2 present this framework and different visualisation methods employed (such as IDEF0 and Sankey diagrams) for presenting the findings to foundries. The audit framework provides a simple step by step approach to foundries to capture their resources consumption, which when coupled with a Pareto style analysis, the various subsystems can be ranked with regards to the energy consumption, establishing in this way which subsystems are best to focus improvement efforts.

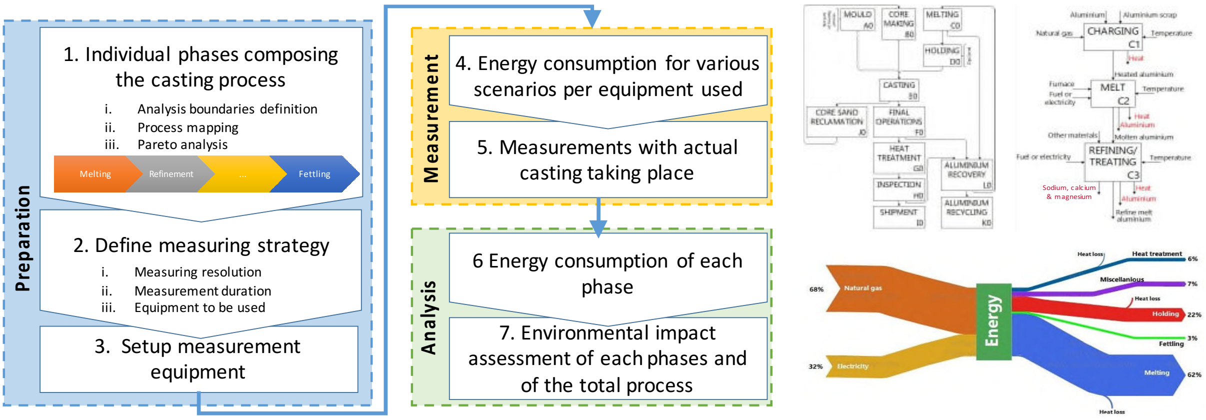


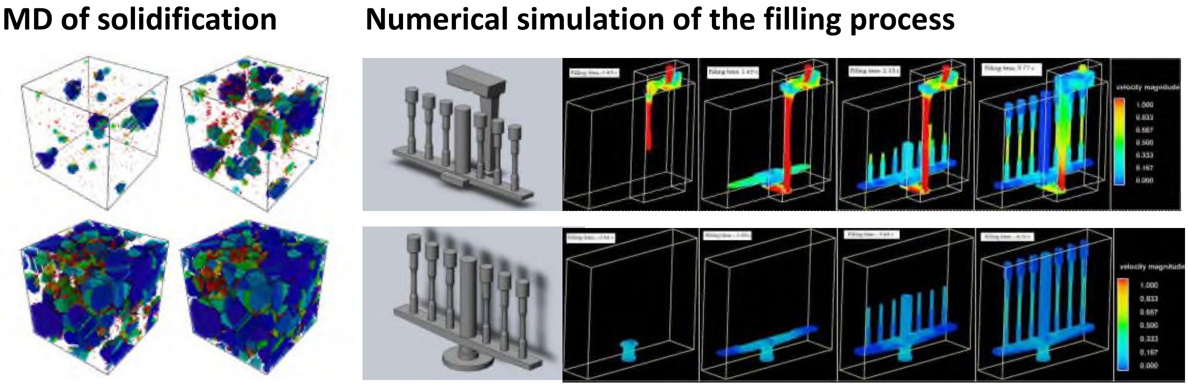
Figure 2: Energy audit framework and visualisation of results [7]

4.2 Modelling and simulation

The energy and resource efficiency can further be improved, minimizing at the same time the resources needed for extensive experimentations and use of assets through the use of modelling and simulation. Depending on the aspect of the process to be improved, different modelling and simulation methods can be used. In the context of the SiB projects, simulations were used for assessing improvements that can lead to reduced use of resources (materials or energy) at fundamental level using for example molecular dynamics, at the machine and process level using computational fluid dynamics and finite element analysis all the way to the macro-level modelling operations using discrete event simulation and agent-based modelling. In the following paragraphs, examples at the different levels will be proposed.

4.2.1 Fundamental material science

Molecular dynamics (MD) provides high resolution information while no ab initio assumptions are required for the physical system under examination. It is the ideal simulation technique for investigating phenomena such as the nucleation process during solidification. In the context of the SiB projects, MD were employed to investigate the effects of the cooling rate and pressure on the properties of solidified aluminium and presented at TMS 2020 conference [8]. The cooling rate significantly affects the grain nucleation and growth as well as the grain distribution in the solidified structure. Therefore its value should be thoughtfully controlled in order to obtain the desired material properties. On the other hand, pressure increases the melting point, increases the growth rate but does not significantly alter the final average grain size. This analysis can help determine the cooling rate that can minimize the development of internal defects [9]. This can have multiple benefits, firstly because the exact energy required for melting the material can be managed and the critical temperature above the melting point can be precisely predicted, as well as the energy required for the cooling and solidification. Indirectly by minimizing defects, the process yield is increased, thus less discards and recycling and thus reduced embodied energy and the associated emissions.



MD of solidification

Numerical simulation of the filling process

Figure 3: Modelling and simulation (left) Molecular Dynamics of nucleation process [8] and (right) computational fluid dynamics of a traditional and counter gravity casting [7]

4.2.2 Designing more efficient casting systems

As highlighted in the introduction, the SiB philosophy suggests using high-quality feedstock, only melting what is required and crucially only when it is required. The well-thought design of the casting system, further to the improvements on the quality of the final castings, can have multiple benefits with regards the use of the available resources such as:

- considerable improvements with regards the use of material, an optimised casting system design can result in less material being recycled, thus reducing the embodied energy of the material and the associated emissions;
- reducing the critical superheat temperature that the material needs to be maintained at for assuring that the moulds are filled before it starts solidifying;

As part of the SiB projects, various elements of the casting systems have been thoroughly investigated and correlated to the energy and resource savings. Indicatively, Papanikolaou et al. [10] used computational fluid dynamics (CFD) to investigate and validate the potential of running and gating systems proposed by Campbell [11] to deliver enhanced quality castings. Salonitis et al. [12] used CFD as well for designing the casting system and simulating the filling process, and integrated this model to a discrete event simulation model for optimizing the productivity of the whole foundry.

Finally, simulation can be used for the validation of the indirect energy savings. Salonitis et al. [7] compared gravity and counter gravity runner systems and their implications to the energy consumption using CFD (figure 3, right).

4.3 Life cycle assessment

For assessing the environmental impact of the processing of a casting, the life cycle assessment method can be used. In the context of SiB projects, research was focused in identifying the appropriate boundaries of such analysis, the environmental impact assessment of the manufacturing processes is possible, allowing at the same time to identify the importance of the manufacturing. Salonitis et al. [7], through the use of life cycle assessment compared in conventional gravity sand casting process with the CRIMSON process for the case of manufacturing an ASTM standard tensile test bar. Energy audits for collecting data for both cases was used that was based on the developed framework. It was shown that recycling sand and metal can reduce the environmental impact of the casting process, with 62% of impact reduction when using recycling in the CRIMSON process and 60% of impact reduction for conventional process. The same approach was followed for the case of casting a housing filter, and similar reductions levels were achieved [12].

The contribution of the production of the raw material and the manufacturing process in the life cycle of a product was also investigated in detail through the use of life cycle assessment methods. For example, for the case of an automotive component two different materials (grey iron and aluminium) and different casting methods were audited as to identify the environmental impact credentials of the different combinations [13, 14]. Critical for the understanding and the analysis required was the development of detailed Sankey diagrams that allowed identifying the "hot spots" in the process chain. One of the key conclusions of this work is that the lightening of a vehicle, through the use of lighter alloys, requires significant amounts of energy during the manufacturing of these alloys, extending the break-even period before the lightening starts paying back.

4.4 Industry 4.0 – moving to Foundry 4.0

In the context of SiB projects, new trends and technologies were also investigated. Industry 4.0 integration at foundries has only recently begun, and it has yet to be thoroughly investigated. Primitive techniques such as remote maintenance via Virtual Private Networks (VPNs) or Machine to Machine (M2M) communication are already in use, and there is massive interest in enabling more of these approaches in the next generation of foundries. There are nine critical elements that form the backbone of the smart foundries namely, (1) Industrial Internet of Things (IIoT), (2) Additive manufacturing, (3) The cloud, (4) Cybersecurity, (5) System Integration, (6) Augmented reality, (7) Autonomous robots, (8) Simulation and (9) Big data and analytics (Figure 4). By implementing the abovementioned methods, traditional foundries can be transformed to the smart foundries.

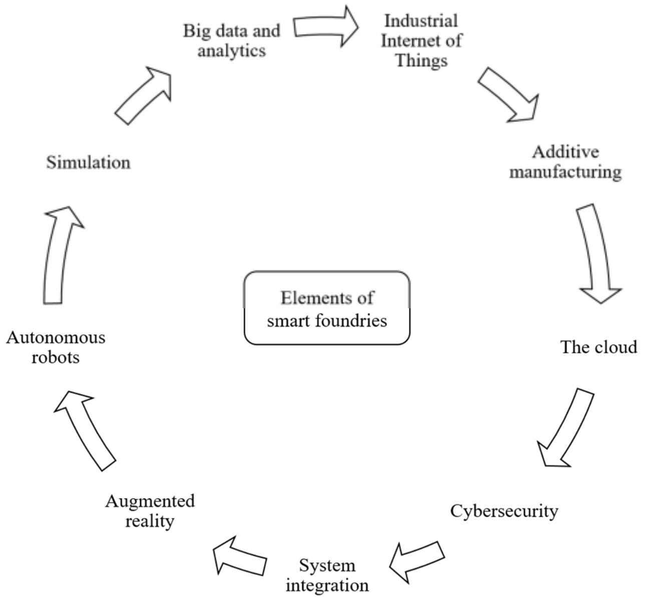


Figure 4: Nine pillars of the smart foundries [15]

In the scope of the SiB projects, one of the key elements is utilising the additive manufacturing processes for 3D printing of sand moulds for CRIMSON process. Specifically, Binder jetting process is used for producing complex shapes of the sand moulds in relatively shorter time frames [15, 16]. Such a process is claimed to save up to 75% of the manufacturing costs.

In this technique a CAD model of the mould is fed as an input to the 3D printer. The platform is initially covered in a coating of powder (sand). After that, the print head sprays a binding agent, producing the part's initial layer. The platform is then lowered to a certain height as specified to the printer, and the procedure is repeated for each subsequent layer until the entire 3D part has been created. Using a brush or pressured air, the unsolidified powder is removed off the printed component [17].

Other Foundry 4.0 techniques involve, utilization of RFIDs (Radio Frequency Identification in the foundries. At many levels, RFID may be utilised to establish a sequence and automate control. A pre-mixing sequence may be defined in a sand mixing machine using RFIDs. This not only allows for the precise use of material, but it also allows for the storage of data related to the material consumption and utilisation on a PC available at a distant location. This can help to cut down on waste and improve the process. Similarly, QR codes can be embedding withing a casting part which can be used to trace and identify the life cycle of the particular casting right from the production to the end-of-life of the product.

4.5 Decision making tools

Support for decision making in manufacturing plants (including foundries) is particularly valuable considering the complex and multi-disciplinary nature of such systems. The optimal choice is often a compromise among dozens of indicators with contrasting requirements: e.g. process parameters optimal for cost and environmental performance can correspond to poor productivity and quality set-points. Although often past experience is considered a valuable and important aid in decision making, objective measures based on established methods that combine into a unique score the indicators (e.g. TOPSIS, ELECTRE, PROMETHEE, COPRAS, VIKOR, etc…) provide more confidence. Within Small is Beautiful, the TOPSIS technique has been used to compare the environmental sustainability of different casting gating systems [16].

Unfortunately, the simple application of Multiple Criteria Decision Analysis (MCDA) methods may still be problematic when multiple decision makers are involved, since they can disagree about the type of metrics to include and their relative importance (or "weight"). In such cases the ranking of possible alternative options will be performed based on a specific weight distribution that may be only a time-consuming compromise that might fail to show the "big picture". Future different priorities can lead to different rankings where the exercise must be repeated. In these cases, it is advisable to perform at least a sensitivity analysis that can provide insight about the robustness of the local solution. To provide a more comprehensive answer that maps quickly a large spectrum of points of view without involving the decision makers in setting the importance of metrics, a method to automatically weight categorised metrics has been devised to be chained to classic MCDA methods (Fig 5). Three, pre-set weight distribution laws (called "halving", "quadratic" and "first two") are applied to all the permutations of the selected categories, providing detailed maps of the complex decision making space highlighting trends, corner cases and trade-offs. One example is shown in Figure 6.

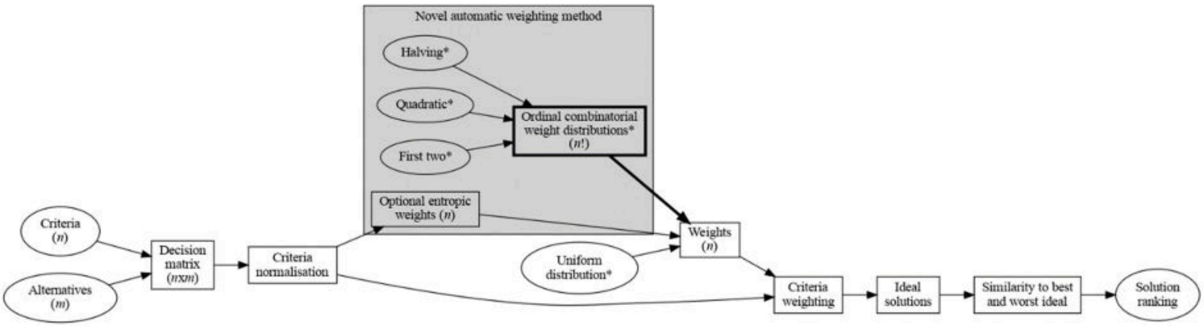


Figure 5: Process flow of the automatic weighting method for categorised metrics combined with the TOPSIS tecnique [18].

This method has been applied to the material selection of automotive parts produced by HPDC processes [18] and to assess the competitiveness of additive manufacturing in building sand moulds for metal casting [16].

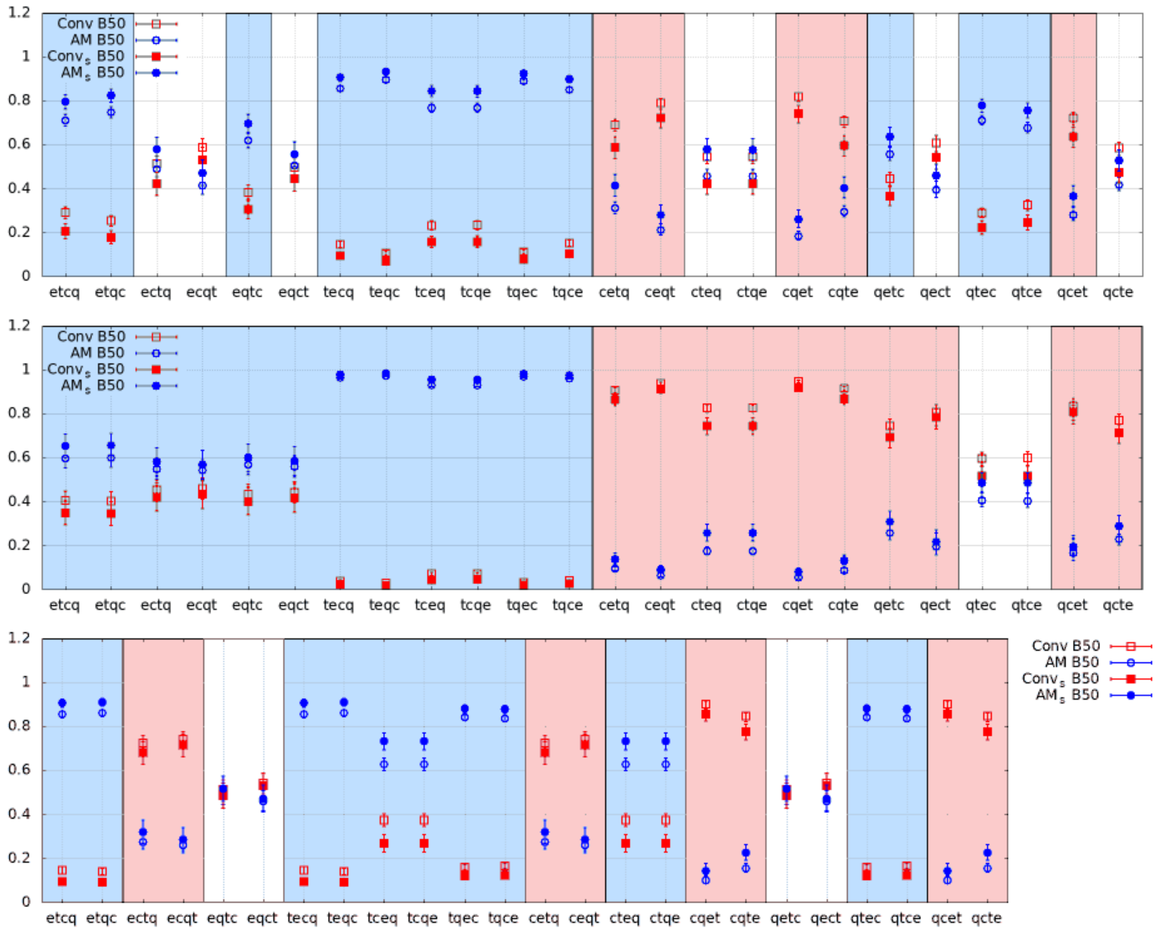


Figure 6: Example of high-resolution maps where conventional ("conv") and Additive Manufacturing (AM) of sand moulds for metal casting are compared combining into a unique score (on the vertical axis) metrics categorised in the areas of environmental sustainability (e), time (t), cost (c) and quality (q). The order of the initials for each category in the labels on the horizontal axis determines their relative importance (or "weight"). Three weight distribution laws are represented. The subscript "s" indicates an analysis performed considering entropy weighting. "B50" indicates that this case has been solved for batches of 50 moulds [16].

4. Bringing everything together and conclusions

The tools that were investigated in the context of SiB projects aim to help foundries to introduce energy efficiency improvement strategies. The following schematic indicates the way these tools are linked to each other, and in a way the sequence with which these needs to be used on their net zero journey.

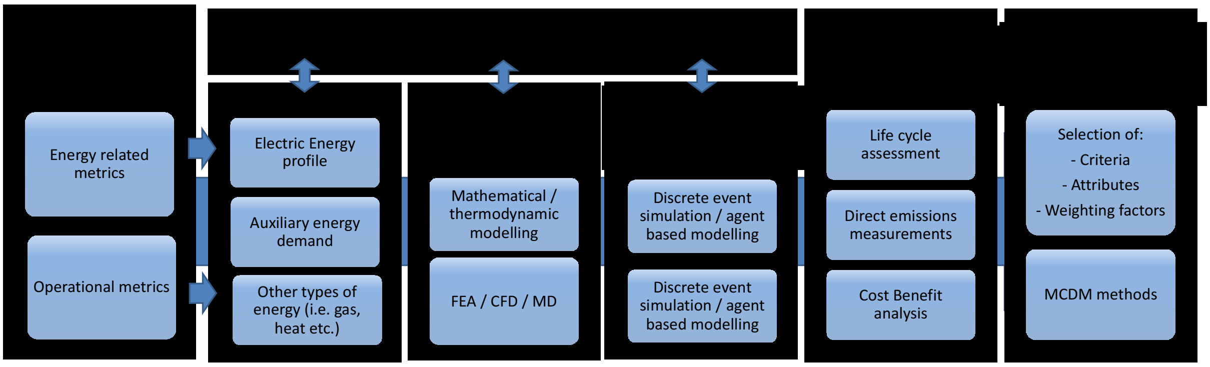


Figure 7: The SiB toolbox.

At the second phase of the SiB2 project, the COVID-19 pandemic "hit" the world. This resulted in disruptions in the operations of all manufacturing supply chains. This was also an opportunity to assess the resilience of the foundries sector, and an initial survey was undertaken to assess how foundries responded. The results of our survey were presented in TMS 2020 conference [19] and show that the foundry sector has successfully adopted and followed the COVID-19 measures such as periodic temperature checks, social distancing, functioning in set groups, and work shifts to guarantee minimum employee interaction. However, this has raised the total cost of manufacturing, which, when paired with a little smaller market for their products, has made it difficult for firms that are already struggling to make ends meet. It is thought that this will have a detrimental impact on the survival of some foundries.

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