Enhancing the introduction of green practices in foundries using machine learning

Gianluca Fratta[1] [0009-0005-7388-8746] and Andrea Rossi[1] [0000-0003-3822-8169]

[1] University of Perugia, Via G. Duranti 93, 06125, Perugia, Italy

Abstract. The environmental impact of manufacturing industries has been deeply investigated in the last decades, showing the necessity of adopting solutions that could help reduce it. In this context, green practices represent an interesting option to partially or totally address the problem. However, their integration into manufacturing processes and lines is far from being simple. Indeed, even though modern tools provide intriguing solutions for assessing the impact of green practices on the manufacturing process, a thorough testing phase is essential. In this scenario, companies struggle to understand how to implement these technologies correctly in their plants, despite the interest generated by their potential benefits, often leading them to abandon the idea of adopting green practices. In this context, modern technologies such as machine learning and artificial intelligence represent promising tools that, when used jointly with classical methodologies, can help address this conflicting situation.

In the present work, we focused on the case of ferrous foundries, an industrial sector currently facing significant challenges in reducing its environmental footprint. As a base for this study, we used the experience gained during the experimental campaign carried out within the Green Casting Life project to formulate an initial framework showing how machine learning models, along with the results provided by tests on an industrial scale, can support better decision-making and reduce uncertainty linked to the adoption of green innovations. Through survey data collected from European foundries, we tried to identify key features related to companies, processes, and products, which can be used to cluster foundries with similar conditions and challenges. The idea is that such clustering could enable a more targeted and feasible implementation of specific green practices—such as the use of inorganic binders—to guide foundries toward sustainable transitions while minimizing disruption and risk.

Keywords: BREF, Green Manufacturing Practices, Green Innovation.

1 Introduction

The manufacturing industry is living through a period of significant changes. Over the past fifteen years, the development of new technologies and growing focus on the environment, workers, and community well-being, along with the significant challenges that arose in the global scenario, have forced manufacturing industries to rethink their production [1] [2]. In response to this complexity, industries started a process of digitalization with the aim of improving efficiency, reducing their expenses, and increasing their flexibility. This phenomenon is unanimously indicated today as Industry 4.0: this concept originated from the German industry, and its essence is the use of technology for efficient production [3]. As shown in [4], resilience and sustainability are improved by the adoption of Industry 4.0, especially when more technologies are integrated, and considering the current global scenario, these improvements could represent a significant advantage. As previously stated, one of the driving forces of this revolution is increased attention to environmental and human health. The need to adapt to new regulations promulgated with the aim of opposing climate change and pollution has made these topics fundamental for the industries.

In the European context, the European Union released in 2010 the Industrial Emissions Directive (2010/75/EU) [5], a document that commits European Union member states to control and reduce the impact of industrial emissions on the environment. The directive is fulfilled through the BREF, written by the EU-BRITE (European Bureau for Research on Industrial Transformation and Emissions), which describes industrial processes, emission and consumption levels of applied techniques, and the best available techniques for integrated prevention and control of pollution from all the different industrial activities. The last release of the BREF was in October 2024 [6]; starting in January 2025, the companies will have four years to adapt to these new requirements.

However, studies such as [7] agree on the fact that companies worldwide often find implementing the changes required by the new regulations challenging. This is due to the different issues, mainly economic and technical, that arise when a new technology is introduced in an existing plant without correct planning. Clearly, such complexity necessitates meticulous management. Due to the size of this problem, a possible solution could be the use of new technologies, such as Machine Learning (ML), to simplify the introduction of new, greener technologies or techniques in manufacturing industries, aiding in the evaluation of costs, times, and strategies to adopt. The leading idea is to train models to predict how a certain green practice could perform in a specific company, based on features related to the process and the products realized.

The goal of this paper is to summarize how manufacturing industries worldwide, but foundry industries in more detail, are facing the introduction of green manufacturing (GM) practices by looking at various pieces of literature. In addition to this, based on the observations collected during the Green Casting Life project—which aims to verify the possibility of introducing inorganic binders, a green practice, in ferrous foundries—a framework to facilitate green practices adoption using ML is presented.

The work is organized as follows. In Chapter 2 is presented an analysis of the state of the art of the green practices, while Chapter 3 presents a description and analysis of the BREF and the BATs and some ideas proposed about how to enhance the introduction of green practices in the foundry industry using ML. Chapter 4 summarizes the work presented and collects some ideas for future development.

2 State of the art

To get a clear picture of what role green practices play in the manufacturing industry right now, we looked first for papers that discuss about the topic in the manufacturing industry to gain a more general view, and then we went further in depth for applications in foundry industries.

2.1 Green Practices, Green manufacturing Practices and Green Innovation

Starting with the basics, the first thing that was searched was the definition of green practices. According to [8], green practices are defined as those that "improve energy resilience, water efficiency, sustainable acquisition/lifecycle management, and electronics stewardship."

This definition is quite general: as observed, the concept of green practices is wide, and it is meant to be applied to different fields. For instance, by searching "green practices" on Scopus, the results obtained regard several kinds of sectors: building, supply chain, healthcare, etc. Due to this, to better meet the purpose of the research, the analysis was focused on the area of green manufacturing practices. According to [9], when the term green is applied to manufacturing, "the general idea of green manufacturing is a process or system that has a minimal, non-existent, or negative impact on the environment.". This definition implies that we can view green manufacturing practices as those that promote this concept. However, what makes a green manufacturing practice challenging to implement? According to literature, there are different reasons.

In the last years, different works have analysed this problem, aiming to identify the main barriers that limit the adoption of green manufacturing practices in industries. The work presented in [10] provides an interesting overview of the barriers related to the implementation of green manufacturing practices in the Indian industries, especially the small and medium enterprises.

In the paper, the authors conducted a review to identify and categorize the primary obstacles to the adoption of green manufacturing practices in India, a particularly intriguing scenario given its status as a developing country. Indeed, while developed countries like the US or EU have made significant progress in implementing green manufacturing practices recently [11], developing countries continue to face significant challenges. The study identifies 25 barriers to GM implementation, which were then grouped as regulatory, core (barriers related to lack of internal abilities and strategies), and external. The study ranked the categories and barriers and revealed their causal relationships. The results show that among the barriers to implementing GM practices in Indian SMEs, the five most critical are lack of research and development, failure in eco-design, poor supply chain management (core), lack of accreditation (regulatory), and absence of market diversification (external). The ranking of the categories shows that the core category is the most critical among the others considered.

It is clear from this result that the successful use of GM practices depends on how well the industries can plan and research to adapt to the changing market and regulatory conditions. However, that is not all the firms' fault.

In [7] it is discussed how companies and society need to change in order to adopt new technology: "Any new solutions being developed must take into account the complexity of the interdependencies between different types of actors with different backgrounds, as well as the need for knowledge development and institutional reforms." Furthermore, "the need for systemic changes may be particularly relevant in the case of green technologies, such as zero-carbon processes in the energy-intensive industries.". The lesson that came from this paper is that the possibility of introducing a certain technology (especially if "green") is often influenced by its degree of novelty. Therefore, all green practices have problems when launched and gradually become more accessible as documentation and knowledge about how to manage and apply them increase. For instance, renewable energies initially struggled to succeed, but nowadays they are well documented and studied, and the possibility of integrating them with the aid of AI or ML to increase their efficiency is widely discussed and carried out. These technologies can be used in the renewable energy field to obtain economic predictions [13] or to predict the availability of natural resources such as wind or sun [14]. In other cases, as the one described in [15], AI can be used to implement AI-based energy management systems that ensure renewable energy integration and energy efficiency improvement. A lot of research is also being done these days on how ML and AI might be able to help applications that are not working very well right now, like the storage of clean energy using fuel cells [16].

Considering this, an important discerning feature that makes a green practice difficult to implement is its novelty and disruptiveness. Thus, for the purpose of this research, the attention was then focused on a specific group of green practices: Green Innovations (GI). The literature contains different definitions for this concept.

According to [17], a green innovation is "a hardware or software innovation that is related to green products or processes, including the innovation in technologies that are involved in energy-saving, pollution-prevention, waste recycling, green product designs, or corporate environmental management.". Other interesting definitions are provided by [18], which describes a green innovation as "a novelty used in technologies that incorporate energy saving, pollution prevention, waste recycling, green product designs, and corporate environmental management," and by [19], which considers green innovations as "the transformation of the operations and processes in such a way that it benefits the natural environment.".

This last definition clarifies an important point, which is the necessity, in some cases, to transform the operations and processes already existing. Given this, it becomes clear that implementing green innovations in a manufacturing industry can represent a complex issue that requires in-depth analysis.

In particular, among the industrial sectors most affected by this issue are foundries. Recently, this type of industry has had to face numerous changes due to the highly impactful nature of its processes [20] [21] in an effort to reduce its environmental footprint. However, often the solutions necessary to achieve this goal have proven to be costly and complex to manage due to technological limitations. The case of ferrous foundries is particularly interesting because even among the BATs indicated in the BREF, there are some whose application is quite complex, despite the undeniable environmental benefits they would bring. At the same time, the recent economic crisis reduced their investment possibilities. In light of these circumstances and the strategic role that foundries play in the European economy, it is worth exploring the use of ML to facilitate the adoption of new green practices in this sector.

2.2 Green practices in the ferrous foundry industry

Overall, in recent years firms seem to understand the importance of this necessary transition. In some cases, they act to increase their competitiveness in the regional and global scenario; in others, they are forced to walk this to survive. This situation applies to European industries. An important point that has emerged in the last years is the necessity of increasing their environmental sustainability to ensure the health of the population and reduce the degradation of the natural resources. In 2024, the European Commission approved a new version of the BREF, a document that defines new criteria in terms of emission limits for industrial activities, pushing them to move toward the application of new technologies to reduce their environmental footprint. This new regulation follows the indication contained in the Industrial Emission Directive, a document introduced in 2010.

Among the technologies enlisted in the BREF (that are indicated as BAT in the document), several of them present a certain degree of novelty, which makes them hard to implement at the current state of the art. Let us consider the case of the casting industry. First of all, it is necessary to make a distinction. The foundry firms can be divided into two main groups: ferrous foundries and non-ferrous foundries. The first collects the foundries that produce steel and iron castings, while the non-ferrous foundries produce castings made with alloys of copper, bronze, aluminium, and so on.

Our research is focused on the ferrous foundries, which present features that make them particularly interesting. First, the majority of the castings produced in Europe are made of ferrous alloys [22]. Given this, ferrous foundries are considered highly strategic due to their significant impact on the economy and society. Second, an important difference that distinguishes ferrous foundries from non-ferrous foundries is the temperatures needed for the production process. Ferrous alloys, indeed, require higher temperatures for melting, between 1380°C and 1420°C. In comparison, aluminium alloys, which are the most produced among the non-ferrous metals, have a melting temperature that is around 700°C. Due to this, introducing energy-saving or emission-reduction practices in non-ferrous foundries is less challenging, while changing technical habits for ferrous foundries is hard. For instance, in [23] the impact of the scheduling on the energy consumption and pollutant emissions is analysed.

Considering its delicacy, the introduction of green innovation in this scenario is a challenging, but necessary process. However, as shown in [24], the ferrous foundries seem to understand this necessity. In the paper, the results obtained from a survey sent to more than 400 ferrous foundries from 8 European countries are analysed with the main purpose of understanding their production habits. The survey was part of the Green Casting Life project, which aims to verify the feasibility of introducing inorganic binders, a green innovation, in the manufacturing of ferrous castings. Among the others, the foundries were asked about green practices, their pros and cons, and their interest in adopting them. The responses obtained are promising: even if only 15% of the interviewed foundries have tried or used inorganic binders, 73% of them are strongly interested in testing them and other green practices to enhance their environmental performance. In addition to this, the foundries enlisted the reasons that push them, revealing that the main drivers are environmental requirements, health requirements, and economic factors. On the other hand, the foundries identified barriers to the introduction of green practices in the technical, economic, and process areas. This confirms that the presence of technical issues related to the introduction of green practices is the main concern of firms.

3 Methodology

In the following section, with a more specific focus on the case of the Green Casting Life project, we will analyse some of the BAT contained in the BREF document, and then we will propose a preliminary framework on how to facilitate the adoption of these practices by companies.

3.1 The BREF for ferrous foundries

To identify the possible green innovation practices that interest the ferrous foundries, we started an analysis of the BATs listed in the latest "Best Available Techniques (BAT) Reference Document for the Smitheries and Foundries Industry" (SF BREF) [25], published in 2024.

The SF BREF contains 52 BATs that regard both foundries and smitheries. Among these, 10 regard both the industries, 35 regard the foundries, and the remaining 7 regard the smitheries. Appendix A summarizes the 41 BATs for the ferrous foundries, grouped by topic. Since many BATs suggest multiple solutions for each environmental issue, a full analysis of the SF BREF would represent a significant effort that goes far beyond the purpose of this work. Therefore, we focused on three specific practices whose use and application are barely documented in the literature: inorganic binders, spent sand reuse, and environmental management systems. A summary of them is reported below.

- **Inorganic binders**: Inorganic binders are compounds made from sodium silicate or geopolymer, which are used to produce molds and cores with lower emissions compared to traditional organic binders. Indeed, they do not release any harmful organic emissions because of their chemical composition, which is carbon-free. While their use is spreading in aluminum foundries, their adoption in ferrous foundries is limited due to technical challenges, such as the increased strength at high temperatures, which makes the sand removal harder, and the moisture absorption, which compromises the binding effect and reduces the shelf life of the cores and molds. In comparison to organic binders, these issues represent a significant problem for foundries, which, in the case of adoption of this technology, will be forced to change their production habits. For instance, cores and molds produced using organic binders can be stored for weeks or even months, while in the case of inorganic binders, this time drops to a few days. and Despite these issues, inorganic binders are economically competitive and are included in BAT 25 to reduce pollutant and harmful gaseous emissions coming from the foundry process. Research projects like Green Casting Life are currently studying the possibility of overcoming their technical limitations by testing some inorganic binders directly in ferrous foundries.

- **Environmental Management System**: EMS is indicated in the SF BREF as a tool that can help companies manage the environmental impact of their production by setting goals, monitoring performance, and improving sustainable practices. According to the document, they can be built following the ISO 14001 standards or using the already existing European Union's Eco-Management and Audit Scheme (EMAS). A complete EMS for foundries should cover areas such as input/output inventories, chemical management, energy efficiency plans, and water and waste management, etc. Despite their benefits, EMS implementation is far from easy because of the high complexity of the process involved and the large number of parameters that must be monitored. In this scenario, emerging technologies like digital twins could help make its adoption easier, addressing this type of resource management problem in the manufacturing industry efficiently, as indicated in [26].
- **Spent sand reuse:** For the manufacturing of cores and molds, foundries use silica sand, which can be reclaimed a limited number of times before its chemical and physical properties degrade. This waste product is called spent or waste foundry sand; according to [27], 6 million tons of spent sand are produced annually in the EU, making it the first solid waste produced by foundries. Its management is costly and environmentally problematic; therefore, the SF BREF suggests improving the reclamation processes to reduce the production of solid waste and to consider the employment of the spent sand as a raw material in construction (the manufacturing of cement and bricks) or road building. However, this second alternative is often problematic because the variable chemical composition of spent sand can negatively affect the quality of these products. This problem leads to various studies [28] [29] exploring the use of AI and ML to predict final product performance, aiming to make these processes more reliable. Table 1 summarizes the features of these three practices.

3.2 Identifying the right green practice

From the BREF document, foundries have no clear direction about which best practice is more suitable for their case in terms of type of production process, type of alloy, type of mould etc. The role of the present research is to define a framework that may be utilized by companies to understand which green practice suits them the most, both in terms of environmental achievement and in overcoming application barriers. The next step is to choose the best practice for each foundry case, as not all practices may be directly applicable or yield the same results, especially if no prior experiments were done. Furthermore, the Green Casting Life project environment could be a great opportunity to gather data and test how the proposed framework would perform.

Table 1. Salient features of the green practice considered.

Practice	Description	Challenges	ML application
Inorganic Binders	Low-emission alternative to organic binders for moulds and cores	Poor performance at high temperatures, moisture reduces shelf-life	Predicting optimal binder formulations for specific casting conditions; process optimization to minimize defects
EMS	Systems for managing environmental impact (e.g., ISO 14001, EMAS)	Complex implementation in foundries; integration with operations	Anomaly detection in environmental metrics; predictive maintenance; optimization of resource use (energy, water, emissions)
Spent sand reuse	Recycling used sand in construction and other sectors	Residual binders/additives affect product quality	Predicting mechanical properties of final products (e.g., concrete) based on sand composition; classification of reusable sand batches

The idea is to identify various groups of foundries that may respond in the same way when a certain green practice is applied within their production. In this way, we may be able to improve the spread of the use of a certain green practice by speeding up the testing phase and the evolution process. We could be able to run pilot test cases on single foundries to see which objective a green practice may achieve and how it may develop to increase its performance. Based on the feedback of each test, we should be able to define the right procedure or process, the requirements (in terms of equipment, etc.), and the financial impact of introducing that practice within a new company with respect to the environmental contribution. Moreover, by using the groups mentioned above, it is easier to identify the companies better suited to adopt the practice.

From this, finding the right composition of the groups/clusters of foundries is a crucial aspect and should be carried out carefully to avoid unwanted results and to make companies able to trust the procedure. In the following, we want to introduce an approach that departs from what one may think is the easiest way, such as classifying foundries based on the alloy or the process type. Indeed, the above procedure could work, but since the variables that may differ from one company to another are a lot, we want to introduce another method that is able to consider multiple variables simultaneously. The method involves the utilization of machine learning to determine to which group a certain company belongs.

Starting from the results of the survey conducted, the first step is to define which should be the variables involved within the classification process. Of course, all the information collected using the part 1 question of the survey should be included (type of alloy, annual production, customer sector, moulding system, sand and binder system, process type, recovery on reclamation, surplus sand treatment), and they should be described using one-shot representation. Furthermore, it would be useful to go more in depth on some of these and even distinguish the different types of production within the same company (for example, a company may produce both steel and cast iron) or also distinguish the type of products, since a certain practice could be ineffective or inapplicable for a certain product. For instance, in the case of inorganic binders, the results of the application of the practice may be different depending on which sand is being utilized or what the characteristics of the product are, such as weight, volume, dimension, etc. Expanding the layer of analysis to the product type allows us to facilitate the data acquisition aspect.

In Table 2, we report a preliminary example of the variables that should be considered for each group of foundries, or even better, group of products, that may see applied the same green practice with similar expected results and implementation barriers. We divided the variables into company-related, process-related, and product-related. Furthermore, the possibility of having contacts with many foundries might be useful to gather data to build a database that may help establish the model. For instance, it would be useful to organize another survey to build a more comprehensive database that does not consist of a single row for each foundry but as many rows as the number of different types of product families (i.e., exhaust manifold, housing, etc.) for each company. In this way the number of entries in the database may grow to a number that can be considered sufficient to build and train preliminary machine learning models.

From this point onward, we could identify two possible ways for continuing to develop the model: one oriented towards supervised learning, while the other is oriented towards unsupervised learning or clustering algorithms.

Table 2. Salient features obtainable from the analysis of the survey.

Dimension	Variables
Company	production capacity, metals, customer market, surplus sand treatment
Process	metal, moulding process, moulding sand, moulding binder, sand reclamation
Product	alloy, family, part weight, part volume, dimensions, core process, core sand, core binder, core weight, core volume, pouring temperature, pouring duration

The supervised learning approach would need an effort from the foundries involved in the Green Life Project in terms of experimentation of a certain practice under observation, and then, based on the outcomes, it would be possible to group similar results and utilize this information as a label for our database. Of course, this would require an effort from the foundries in the group and from the project coordinator, who would need to monitor all the experiments, collect the results, and organize them in the database. Once the database is completed, the next step would be to train a machine learning classification model to predict to which group a certain company/product should belong and, consequently, which results would be achieved based on the green practice implementation. The ML algorithms that could be used for this purpose are decision trees (Random Forest, XGBoost etc.) or neural networks (Multi-Layer Perceptron or Deep Neural Network) depending also on the dimension of the dataset that is obtained. The unsupervised approach would be easier in terms of implementation because it would not require running several experiments among the foundries involved in the project, but it would instead aim to identify clusters of companies/products. Even in this case, the most suitable clustering technique should be chosen after the database is available and its characteristics are clearer.

Once a model has been developed and tested, it will allow the facilitation of the implementation of the green practice under observation in other companies outside the Green Life Project, contributing to the practice diffusion and enhancing sustainability diffusion. Furthermore, conducting experiments for more than one green practice would be useful to understand the model's flexibility and see if the results and model behaviour change.

In Fig. 1, the steps for developing the framework are shown. The data acquisition and the experiment validation steps are undoubtedly the most challenging and time-consuming, but they are strictly needed for the model building and validation. During the data acquisition phase, in order to gather data with a certain quality, the company involvement and their dedication to the project will be crucial. Moreover, the data acquisition phase will need to be standardized to ensure the quality and avoid missing or incorrect data. The definition of the right procedure for data acquisition and experiment validation will be the next steps of the present work.

Fig. 1. A preliminary framework.

4 Conclusions

In the present work, we addressed the introduction of green practices in foundries. For this purpose, we analysed two main sources: the existing literature and SF BREF, the main document that regulates this transition. The literature was fundamental to understanding the main challenges and barriers that foundries, and in general, manufacturing industries, face when they try to introduce these practices in their production processes. The SF BREF, on the other hand, was useful to understand the technological development of the green practices for the foundry sector, highlighting how the application of the proposed solutions is often insufficiently documented or known to the firms. In light of this, it is clear that applying green practices can become a huge challenge for foundries.

Based on this, we proposed a preliminary framework that could ease this transition. The core concept is that, through a classification approach realised using techniques like ML, foundries can be grouped to predict the impact that the implementation of a specific green practice will have on a certain type of foundry. In this way, the proposed framework could be used as a decision support tool for companies to reach sustainable goals.

The main challenge identified is related to data acquisition and quality, which represent the next steps of this research. To achieve this, deep cooperation with the companies involved in the Green Casting Life project will be required. However, these activities need a strong willingness to collaborate from the different companies and require a lot of time to register their outcomes. Once this step is complete, it will finally be possible to apply and validate the model, enhancing the way foundries commit to adopting green practices.

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Appendix A

Table 3. Schematic classification of the BATs presented in SF BREF, highlighting their position in the document and the topic that they concern.

Section	Group	Topic	BAT
4.1 General BAT conclusions		Overall environmental performance	1, 2, 3, 4, 5
		Monitoring	6
		Energy Efficiency	7
		Noise and Vibrations	8, 9
		Residues	10
4.2 BAT conclusions for foundries	**4.2.1** General BAT conclusions for foundries	Hazardous substances and substances of very high concern	11
		Monitoring of emissions	12, 13
		Energy efficiency	14
		Material efficiency	15, 16, 17, 18, 19, 20
		Diffuse Emission to air	21
		Channeled emissions to air	22
		Emissions to air from thermal processes	23, 24
		Emissions to air from moulding using lost moulds and core-making	25, 26
		Emissions to air from casting, cooling and shake-out processes in foundries using lost moulds including the full mould process	27
		Emissions to air from lost foam casting	28
		Emissions to air from the casting process in foundries using permanent moulds	29
		Emissions to air from finishing	30
		Emissions to air from sand reuse	31
		Odour	32, 33, 34
		Water consumption and waste-water generation	35
		Emissions to water	36
	4.2.2 BAT conclusions for cast iron foundries	Energy Efficiency	37
		Emission to air from thermal processes	38, 39