# Inorganic binders in ferrous foundries: feasibility assessment through a Life Cycle Costing (LCC).

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**Abstract**: With the release of the new BREF (Best Available Techniques Reference Document) for the foundry industry, enacted by the European Union and effective at the beginning of 2025, foundry companies are now required to reduce their environmental impact using the Best Available Techniques (BATs) identified in the document. The goal is to minimize atmospheric emissions of pollutants or toxic substances, as well as resource consumption and waste production. One of the suggested BATs is represented by the use of inorganic binders for the manufacture of cores and moulds. While this technique is becoming an industrial standard for non-ferrous alloy casting production (such as aluminium), challenges are being encountered in the production of ferrous castings (iron and steel). Despite the proven environmental benefits, ferrous foundries still perceive the introduction of this technology as uncertain, given the lack of a shared industrial standard regarding its application. Moreover, as a precautionary measure, foundries remain cautious due to an unclear cost profile associated with the integration of inorganic cores in the overall process. This study aims to fill the gap in both the scientific literature and industrial know-how by proposing a Life Cycle Cost (LCC) framework. This paper presents, categories, and analyses the main costs that a company might incur when adopting this technology. The objective is to provide an overview of the costs and savings associated with this new process, highlighting the economic differences compared to the current industrial standard, which consists of using organic binders. This analysis is intended to support future research on the practical application of inorganic binders and serves as a reference point for companies evaluating the adoption of this technology.

**Keywords**: Life Cycle Costing, Inorganic Binders, Ferrous Foundries, BREF

## 1. Introduction

Sustainability has become a fundamental topic for industry (Leggerini & Bannò, 2025). Over the past few years, led by a growing awareness of the problem, regulations have become increasingly stricter, pushing industries to modify their production habits to fulfil the requirements (Prakash, et al., 2022; Lanzini, et al., 2024).

To achieve this target, firms are required to implement new technologies, which allow them to reduce their environmental footprint. In Europe, the EU published a set of documents called the BAT Reference Document (BREF), which establishes the emission levels and reports the best available techniques (BAT) for minimizing the environmental impact across various industrial sectors.

These compounds are among the BATs recommended to mitigate the considerable environmental impact of the foundry industry (Olmez, et al., 2016). Inorganic binders represent an environmentally friendly substitute to the petroleum-based organic binders currently used in sand mold and core production. Due to their carbon-free chemical composition, they generate significantly lower quantities of harmful and polluting substances during the casting process (Dańko, 2023). Consequently, they are included in the latest version of the Smitheries and Foundries BREF (SF BREF) (EU-BRITE, 2024).

Despite their environmental advantages, the adoption of inorganic binders in ferrous foundries remains limited. Ferrous foundries are the most important foundry sector in Europe, accounting for 80% of the metal castings manufactured annually in Europe (CAEF - The European Foundry Association , 2024). Considering this, the use of inorganic binders could help control the emission of hazardous and pollutant emissions produced during the process (Anwar, et al., 2023).

Ferrous foundries firms are reluctant to adopt this technology: experimental trials were carried out to verify the possibility to use inorganic binders in the ferrous castings production showing limitations, especially regarding the necessity to change the production habits of the company (Czerwinski, 2015). The main challenges come from some technical aspects of the inorganic binders, like their weak resistance to moisture and poor performance at high temperatures, which harm the quality of the sand cores and molds produced (Xin, 2020).

To address these issues, the European Union launched several initiatives, including the Green Casting Life project, aimed at testing the large-scale application of inorganic binders in iron foundries. Results from this project suggest that it is feasible to produce ferrous castings using new inorganic binders under specific conditions (Fratta, et al., 2025). A key preliminary finding is that the overall production cost is comparable to that of conventional processes using organic binders.

However, given the complexity of the foundry process and the numerous variables involved, a comprehensive cost assessment for hypothetical large-scale implementation has yet to be conducted (Saetta, et al., 2021). Moreover, the existing literature lacks such economic evaluations, as foundries often treat cost data as sensitive and strategically important.

Nevertheless, investigating this topic could provide valuable insights for companies considering transitioning to inorganic binders. To achieve this The LCC analysis is frequently applied by companies that face decisions on major investments that affect the whole life cycle of a product (Krozer, 2008).

The literature presents different examples of LCC applications for comparison purposes. (Kokare, et al., 2023) uses an integrated LCC–LCA framework to compare wire arc additive manufacturing and selective laser melting for steel wall component manufacturing with conventional computer numerical control milling. Results show wire arc additive manufacturing offers material savings and becomes more cost-effective with increasing parts complexity and size. The analysis carried out in (Mecheter, et al., 2023) compared direct metal laser sintering to conventional machining, finding that despite higher initial costs, it is economically advantageous for producing complex or customized parts due to reduced material waste and greater design flexibility. A relevant example of the application of LCC analysis to compare conventional and more sustainable manufacturing technology is described in (Kianian, 2019), where the economic feasibility of powder metallurgy for gear production in the automotive industry is investigated. Although the acquisition costs for powder metallurgy were found to be significantly higher due to tooling and equipment investments, the process benefits from shorter cycle times and potentially lower operational costs. This approach highlights how LCC can be used not only to quantify costs but also to support strategic decisions when considering the adoption of innovative, environmentally friendly technologies.

However, a preliminary literature review revealed that no standardized procedure exists for conducting LCC analyses in industrial manufacturing contexts. A search on Scopus using the keywords *"Life Cycle Costing" AND "Analysis" AND "industry" AND "manufacturing"*, limited to the engineering subject area, returned 54 papers. After excluding studies unrelated to manufacturing (e.g., those focused on construction) and filtering for English-language, open-access publications, only 15 relevant papers remained. The period of their publication ranges between 2013 and 2025. Even among these, there was no consistent methodology: each study adopted a different approach and emphasized different cost components. Because of this lack, the ISO 14040:2006 (Finkbeiner, et al., 2006) standard for Life Cycle Assessment (LCA) was used as a conceptual starting point, as further detailed in the following sections.

This lack of standardization underscores the need to define a clear, structured method tailored to the specific features of sand core production in foundries. This paper explores the economic feasibility of introducing inorganic binders in ferrous foundries through a Life Cycle Costing (LCC) analysis, which itemizes and evaluates all costs incurred during each phase of the life cycle of inorganic sand cores used in the production of ferrous castings. The study compares two core-making processes: the conventional cold box method using organic binders and an innovative approach that relies on inorganic binders, requiring both heat and a chemical catalyst to set. The analysis draws on data provided by one of the foundries that participated in the Green Casting Life project, where various inorganic binders and manufacturing methods were tested to identify the most suitable solutions for the company's operational requirements. In light of this, the objective of the presented work is to develop a framework, grounded in LCC methodology, to offer a structured and quantitative economic assessment of the core production process using inorganic binders.

The presented work is organized as follows. Chapter 2 describes the methodology adopted for carrying out the analysis, while chapter 3 reports the economic results obtained. Chapter 4 discusses outcomes and limitations of the research, providing suggestions that could contribute to improving the quality of future research.

## 2. Methodology

To understand the economic impact of introducing inorganic binders into the production processes of ferrous foundries, a Life Cycle Costing (LCC) analysis was conducted. LCC provides a comprehensive framework for estimating all costs incurred throughout a product or system's life cycle, including production, operation, maintenance, and eventual disposal or recovery (Korpi & Ala-Risku, 2008). This method is particularly suited to evaluating technological changes in manufacturing, as it accounts for both initial investments and long-term operational expenses.

In this study, LCC is applied to compare the costs of manufacturing sand cores using inorganic binders with those using traditional organic binders, within a plant employing the green sand process. Given the significant differences in machinery and raw material requirements between the two approaches, LCC is essential for accurately quantifying and comparing their economic implications. The methodological approach adopted in this study is structured into three main phases:

1. *Process identification and modeling*. The analysis focuses on the cores' entire manufacturing process, from the acquisition of raw materials and equipment to the disposal of production scraps. The process was broken down into its constituent phases and modelled using the IDEF0 methodology, which highlights inputs, outputs, and material and information flows. Based on this structure, the fundamental unit processes were identified and used

as the basis for cost attribution. ISO 14040:2006, which provides a framework for Life Cycle Assessment (LCA), was adopted as a reference for this phase, particularly for its emphasis on identifying unit processes and associated flows.

2. *Data collection*. Information on costs associated with each unit process was gathered through interviews with the technical staff of the participating foundry. Attention was focused on process elements that differ significantly between the two core-making technologies. In cases where cost data were unavailable, due to lack of measurement or confidentiality, appropriate adjustments were made to enable integration into the cost model.

3. *Data elaboration and integration*. The collected data were scaled, normalized, and adapted to fit the analytical framework. For missing cost items, their impact on the comparative analysis was assessed. If a missing item was deemed significant, preliminary estimates were introduced. Otherwise, items were excluded from the analysis if they were common to both manufacturing methods and thus not influential in the comparison.

The purpose of this methodology is to provide a preliminary, yet comprehensive analysis aimed at assessing the economic sustainability of the inorganic manufacturing process by identifying its main cost drivers.

## 3. LCC Model Description

The cost model is based on the core manufacturing process typically adopted in ferrous foundries that use the green sand process. In this context, molds are prepared using sand mixed with bentonite, while the sand cores, essential to forming internal cavities in the castings, are produced using core shooting machines.

The first step in constructing the LCC model was the identification and decomposition of all activities involved in core manufacturing, including supporting operations not directly linked to physical production. Based on this analysis, the overall process was divided into three main phases: supply of raw materials and components, core manufacturing, and end-of-life and waste disposal. Figures A.1 and A.2 in the Appendix represent the decomposition carried out by using the IDEF0 methodology, which was used to identify these phases.

Among these, the core manufacturing phase is the most complex and was further broken down into three distinct operations: mixing, core shooting, and core painting. This breakdown applies to both the organic and inorganic binder processes, as they share a common production structure. However, key differences exist in the type of raw materials and equipment used, as well as in the execution of the core shooting and painting operations. In contrast, the preparation of the sand-binder mixture and the management of production waste are similar for both technologies and were treated as common elements in the cost model. Following the process mapping, the main cost drivers were identified. The first distinction that was made is between initial investment costs and operating costs.

The initial investment costs represent all the expenses that the firm incurs to purchase the machinery required for start-up production. This category includes the costs required to buy or adapt the core shooter for the inorganic process and to manufacture the core box, which is the die that is used to shape the cores.
Concerning the operating costs, to evaluate the economic impact of every step of the manufacturing process, they were further decomposed. This decomposition was guided by the principles outlined in ISO 14040, originally developed for Life Cycle Assessment (LCA). The ISO 14040 standard suggests a series of unit processes that characterize each manufacturing process and influence its environmental impact, including inputs and outputs, material and resource flows, transportation, and more. In the context of the LCC analysis, these unit processes were used to associate specific costs with each phase of the core manufacturing process for both binder technologies.

Table A.1 in the Appendix classifies cost allocation across production phases using IDEF0 modeling, dividing them into four categories: 'shared same costs,' 'shared different costs,' 'organic only,' and 'inorganic only.' Table 1, on the other hand, presents a detailed decomposition of the manufacturing process and the corresponding unit processes used in the LCC analysis.

**Table 1: Identified operating expenses**

| Step | Unit Process | Cost item |
|---|---|---|
| Mixing | Raw materials | Sand<br>Binding system |
| | Energy | Sand mixer |
| | Labour | Labour |
| | Maintenance | Cleaning<br>Generic maintenance |
| | Waste | Scrap sand |
| | Transport | Sand<br>Binding system |
| Core Production | Raw materials | Compressed air<br>Gaseous catalyst |
| | Energy | Heat<br>Electricity |
| | Labour | Labour |
| | Maintenance | Generic maintenance |
| | Waste | Scrap cores |
| | Transport | Handling |
| Core painting | Raw materials | Alcohol based paint<br>Water based paint |
| | Energy | Paint mixer<br>Drying oven |
| | Labour | Labour |
| | Maintenance | Generic maintenance |
| | Waste | Scrap cores |
| | Transport | Handling |

To populate the model with reliable data, interviews were conducted with the technical staff of the participating foundry. This approach was necessary to obtain information that is difficult to find in literature or public sources, particularly for cost components specific to the company’s operations.

## 4. Results and Discussion

This section presents the results of the LCC analysis conducted to compare the economic performance of core production using organic and inorganic binders. Subsection 4.1 focuses on the required initial investments, while subsection 4.2 outlines the operating costs associated with each process. Finally, subsection 4.3 provides a discussion of the findings and highlights the limitations of the model.

### 4.1 Initial investment

The initial investment costs were identified based on the experience gained during the Green Casting LIFE project. At the time, the foundry was unable to produce cores using inorganic binders in-house, as it lacked the specific machinery required. As a result, it had to outsource production to external firms.

In general, cores of small to medium size are produced using machines known as core shooters, which shape the sand cores and cure them according to the binder type. The foundry currently operates using the cold box process, in which cores are hardened by injecting a gaseous catalyst, specifically, an ammine, into the core box. In contrast, the inorganic binder process requires both a gaseous catalyst (carbon dioxide) and heat, making the foundry’s existing equipment incompatible without significant modification. Table 2 summarizes the investments required for the two scenarios and their costs.

**Table 2: Initial costs**

| | Cost items | Unit | Organic | Inorganic |
|---|---|---|---|---|
| **Scenario 1** | Core shooter | € | 500,000 | 650,000 |
| **Scenario 2** | Heating unit | € | Not required | 22,000 |
| | Gas Unit | € | Not required | 22,000 |
| | Core box | € | 30,000-50,000 | 120,000-220,000 |

Two possible investment scenarios were identified. The first involves purchasing a new core shooter designed for inorganic production, with an estimated cost of approximately €650,000 for a medium-to-large size machine (40 litres). The second, more cost-effective option consists of modifying an existing core shooter by adding a heat generator and a $CO_2$ blower, each costing around €22,000.

The most significant cost driver, however, is the core box, a critical component that forms the mold cavity for the sand core. In the cold box process, core boxes are typically made of aluminium due to the reduced cost of machining and high durability. This keeps costs relatively low. However, aluminium cannot be used in the inorganic process, as the required heat causes thermal deformation, leading to defects in the cores. For this reason, steel core boxes are necessary. Steel's resistance to heat ensures dimensional stability but significantly increases manufacturing costs. According to the foundry, the cost of producing a steel core box ranges from €120,000 to €220,000, depending on the core's geometry and size. This substantial cost represents a major limitation for the adoption of inorganic binder technology, especially when compared to the lower-cost aluminium core boxes used in conventional cold box production.

### 4.2 Operating and manufacturing costs

Table 3 presents the operating expenses estimated for the two core manufacturing scenarios. The analysis focuses on unit processes with cost differences between the organic and inorganic binder technologies.

**Table 3: Collected operating expenses**

| **Step** | | **Cost item** | **Unit** | **Org.** | **Inorg.** |
|---|---|---|---|---|---|
| **Mixing** | Raw materials | Sand | €/ton | 81.50 | |
| | | Binding system | €/kg | 3.40 | 3.90 |
| | Energy | Electricity | The same applies | | |
| | Labour | Labour | The same applies | | |
| | Maintenance | Cleaning | Negligible | | |
| | | Generic | Negligible | | |
| | Waste | Scrap sand | ~2% of the weight | | |
| | Transport | Sand | Included in the costs of the raw materials | | |
| | | Binding system | | | |
| **Core Production** | Raw materials | Compressed air | The same applies | | |
| | | Gaseous catalyst | €/kg | 5 | 4-8 |
| | | Electricity | - | - | Higher |
| | Labour | Labour | The same applies | | |
| | Maintenance | Generic | Negligible | | |
| | Waste | Scrap cores | ~2% of the cores | | |
| | Transport | Handling | Negligible | | |
| **Core painting** | Raw materials | Paint | €/kg | 1.90 | 7.40 |
| | Energy | Paint mixer | Negligible | | |
| | | Drying oven | - | Required | Not required |
| | Labour | Labour | The same applies | | |
| | Maintenance | Generic | Negligible | | |
| | Waste | Scrap cores | ~0 % | | |
| | Transport | Handling | Negligible | | |

Where a cost component was expected to differ but could not be directly measured, an indirect estimate was derived from available company data. In contrast, cost items that were considered equivalent across both processes were excluded from the comparison, as they do not influence the relative outcomes of the LCC analysis. To increase the transparency of the analysis, Table 3 also includes a brief qualitative evaluation of each cost component. For example, the label "the same applies" indicates that the cost is similar for both technologies, while "negligible" denotes that the contribution of the cost driver is too small to meaningfully affect the overall result. The most significant differences in operating costs stem from two categories: raw materials and energy consumption in specific process phases. The foundry provided cost estimates for the materials required to produce 100 kg of core sand using the organic process. These inputs, along with their respective costs, are summarized in Table 4.

**Table 4: Detail of the raw material costs required for manufacturing a 100 kg core using organic process.**

| | Item | % on 100 kg cores | Cost |
|---|---|---|---|
| **Organic Binder** | Resin A (phenolic) | 0.9% | €2.89 |
| | Resin B (isocyanic) | 0.9% | €3.23 |
| **Sand** | National | 68.5% | €4.67 |
| | French | 29.5% | €3.54 |
| | DMIPA ammine | 0.2% | €0.72 |
| | **Total** | | **€15.05** |

The cost of manufacturing the same core using the inorganic process was evaluated during the Green Casting LIFE project for different inorganic binders, and it resulted in a range of 90% to 114% of the cost required for the organic process. In addition to this, the cost of the paint required for coating the cores must be considered. In fact, the cores made with inorganic binders can't be coated using the water-based paint that the foundry employs in its organic production because of the low resistance to humidity that characterizes the inorganic binders. As a result, alcohol-based paintings must be used, increasing the manufacturing costs and the emissions, as they are organic-based. However, this aspect can't be included in the present analysis, as data for the evaluation is lacking. Concerning energy consumption, the inorganic production requires an extra contribution because of the necessity of heating the core box. It is not possible to precisely estimate this cost, as the foundry did not directly measure it during the process test phase. However, considering its impact on the production costs, a preliminary and rough estimation was made by considering the properties of the core box and the work conditions required for manufacturing a 40 kg core. The data provided by the foundry is collected in Table 5.

Using this data and applying the specific heat equation, the energy required to heat the steel core box was estimated at 312.5 MJ. Given the heat generator's nominal power of 77 kW, the heating phase would last approximately 68 minutes (4,060 seconds). Accounting for thermal inertia and losses (+25%), the actual time increases to about 85 minutes, or 1.42 hours. Using the foundry's electricity rate of €0.16 per kWh, the resulting heating cost per shift is approximately €18. This value is added to the base energy consumption of the core shooter, which is assumed to be the same across both production technologies.

**Table 5: Data used to evaluate the energy consumption of the heat generator used in the inorganic process.**

| Data | Unit | Value |
|---|---|---|
| Core box weight | kg | 5000 |
| Steel, specific heat capacity | J/kg°C | 465 |
| Operating temperature | °C | 140 |
| Heat generator, nominal power | kW | 77 |
| Electricity fee | €/kWh | 0.16 |

Other energy-related differences include the use of the drying oven and air treatment systems. In the inorganic process, oven drying is not required because the alcohol-based paint dries at ambient temperature. In contrast, organic cores that are coated with water-based paint must undergo drying in an oven. However, the energy consumption of this equipment is not currently monitored by the company, and further investigation is needed to assess its financial impact.

Based on the available data and assumptions, the overall operating and manufacturing costs for the inorganic process appear to be comparable to those of the organic process. Although certain elements such as heating and coating introduce additional costs in the inorganic case, others, such as oven energy use, are eliminated. These offsetting factors suggest no substantial difference in total operating expenses between the two methods under current operating conditions.

## 4.3 Discussion of the results

The LCC analysis highlights that, while operating and manufacturing costs for inorganic core production are broadly comparable to those of the organic process, the transition to this technology remains challenging. The main barrier lies in the substantial initial investment required, particularly for steel core boxes, heat generators, and $CO_2$ systems, which significantly increases capital expenditure.

Concerning the limitations of the presented analysis, the primary limitation of this model lies in the unavailability of complete cost data, which prevents the precise quantification of the total expense associated with manufacturing sand cores using inorganic binders.

Nevertheless, the analysis remains valuable in highlighting the most cost-sensitive phases of the inorganic process. These insights can support future efforts to improve its economic sustainability and enhance its competitiveness relative to the traditional organic method.

## 5. Conclusion

This study offers a preliminary yet meaningful assessment of the financial implications associated with adopting inorganic binders in ferrous foundries, addressing a notable gap in both academic literature and industrial practice. By applying a LCC approach, the analysis reveals that, contrary to widespread assumptions, inorganic binders do not necessarily lead to higher daily operating costs. In fact, the overall production expenses are comparable to those of traditional organic processes.

However, the transition to inorganic binder technology remains challenging. The key barrier lies in the substantial initial investment required, particularly for specialized equipment such as steel core boxes, heat generators, and $CO_2$ systems. Additionally, technical limitations persist. Inorganic cores’ low resistance to humidity reduces their shelf-life, constraining production flexibility, while their use in high-temperature ferrous casting can increase post-casting cleaning costs due to sand residue removal. Although these aspects fall outside the scope of the LCC, which focuses on the core manufacturing phase, they highlight the broader operational implications of adopting inorganic technologies.

The analysis is further constrained by data limitations, particularly regarding energy use, maintenance, and labor costs, which were not measured during the Green Casting project. In such cases, indirect estimates or assumptions were applied, and cost elements deemed equivalent across both technologies were excluded from the comparison. Despite these limitations, the study effectively identifies the main cost drivers and economic bottlenecks, offering valuable insight into where future improvements and investments should be targeted.

Looking ahead, the integration of LCC with LCA could provide a more comprehensive perspective, capturing both financial and environmental impacts of technological change. This dual approach would offer a clearer picture of the true benefits and trade-offs associated with inorganic binders in ferrous foundries.

Finally, the findings underscore a key concern: the high upfront costs associated with adopting inorganic technologies may be unsustainable for most foundries. In light of the forthcoming Best Available Techniques Reference Document (BREF) for ferrous metals, policymakers should consider providing targeted financial incentives and technical support to facilitate a realistic and equitable transition toward more sustainable and environmentally responsible casting practices. This work contributes to establishing a foundation for more robust cost assessments and lays the groundwork for future policies supporting sustainable innovation in foundry technology.

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## Appendix A. FIRST APPENDIX

Table A.1: Classification of cost allocation concerning the phases of the production process

| Cost imputation | Component supply | Core manufacturing | | | End of Life and disposal |
|---|---|---|---|---|---|
| | | Mixing | Core shooting | Core Painting | |
| **Shared (same costs)** | | Sand<br>Electricity<br>Labour<br>Cleaning<br>Transport | Labour<br>Cleaning<br>Transport<br>Scraps | Labour<br>Cleaning<br>Handling | Sand disposal |
| **Shared (different costs)** | Core shooter | | Electricity | Energy | Sand reclamation |
| **Organic only** | Aluminium core-box | Organic binder | Ammine | Water based paint | |
| **Inorganic only** | Steel core-box<br>Additional machinery | Inorganic binder | Heat<br>$CO_2$ | Alcohol based paint | |

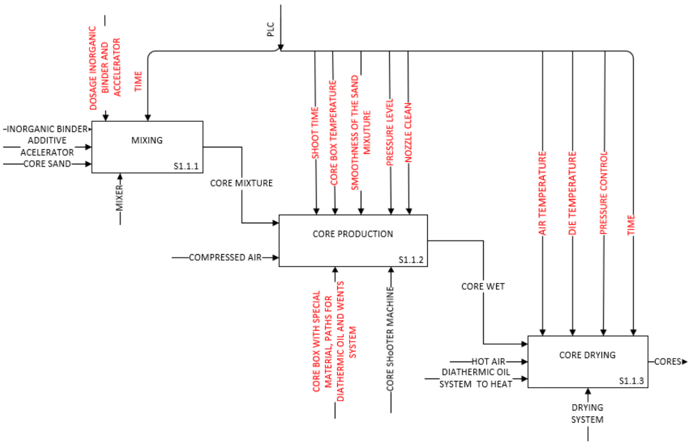

Figure A.1: Core manufacturing carried out in the core shop of the foundry.

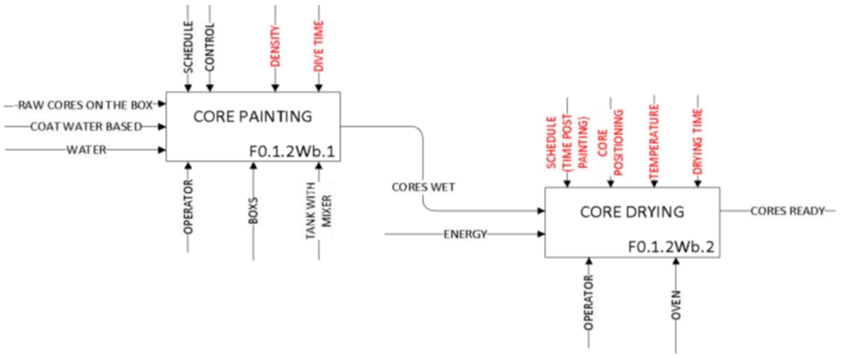

Figure A.2: Core painting carried out in the core shop of the foundry.