

Framework for LCA Analysis of the Introduction of Inorganic Binders in Ferrous Foundries

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Abstract: European foundries are undergoing a significant environmental transition following the issuance of the new BREF (BAT Reference Document) for the sector, which came into effect in 2025. This document imposes stricter limits on atmospheric emissions, resource consumption, and waste production, encouraging the adoption of the Best Available Techniques (BAT). Among these, inorganic binders emerge as a promising solution to reduce harmful emissions in the foundry industry. However, despite their proven environmental benefits and increasing use in the production of non-ferrous metal castings, their application in ferrous foundries remains limited, mainly due to the economic and operational uncertainties perceived by companies. Additionally, there is still no strong consensus on the actual environmental benefits of implementing this new technological process. Various concerns have emerged, such as the potential increase in pollutants during core blowing or the challenges associated with the recovery of core sand after the casting has been removed from the mold. This study arises from the gap in available information, both in scientific literature and in industrial know-how, by proposing a structured framework for Life Cycle Assessment (LCA) applied to the introduction of inorganic binders in ferrous foundries. Based on ISO 14040 guidelines and the ILCD framework recommendations, the developed model enables the assessment of environmental impact throughout the entire production cycle, considering raw materials, the core blowing process, energy consumption, emissions, and the management of recovered materials. Moreover, the framework integrates a comparative analysis between conventional and innovative production processes, supported by literature data and insights from industry experts. The proposed approach aims to provide companies with a quantitative tool to support strategic decision-making and enhance the sustainability of their operations. The expected results will contribute to bridging the existing knowledge gap on the adoption of inorganic binders in ferrous foundries, facilitating the transition towards lower environmental impact solutions.

Keywords: Life Cycle Assessment (LCA), ferrous foundries, inorganic binders, environmental impact, BREF.

1. Introduction

The escalating global focus on environmental sustainability is compelling industries worldwide to critically evaluate and mitigate their ecological footprint (Leggerini et al., 2025). Within the manufacturing sector, the ferrous foundry industry is recognized as a significant contributor to environmental impact, facing increasing pressure to adopt more sustainable practices (Pare et al., 2018). Traditional foundry processes, particularly those utilizing organic binders, can generate substantial emissions and environmental burdens throughout their life cycle (Pare et al., 2018; Fratta et al., 2024). This necessitates a comprehensive understanding and quantification of these impacts to facilitate the transition towards more environmentally benign alternatives like inorganic binders. Life Cycle Assessment (LCA) has emerged as a methodology for holistically assessing the environmental performance of products and processes (Roletto et al., 2024). By encompassing all stages from raw material extraction to end-of-life management, LCA provides a robust framework for identifying environmental hotspots and evaluating the potential benefits of alternative technologies (Herrera et al., 2022).

The principles and framework for LCA are well-established in international standards such as ISO 14040 and further elaborated in guidelines like the International Life Cycle Data system (ILCD) framework (Herrera et al., 2022). LCA stands as a prominent method for the structural assessment of environmental impacts in various sectors (Herrera et al., 2022; Roletto et al., 2024).

Despite the growing body of LCA studies in the broader manufacturing domain (Herrera et al., 2022; Bekker et al., 2018) a notable information gap exists concerning the application of LCA specifically to the introduction of inorganic binders in ferrous foundries. While existing research has explored the environmental impacts of specific aspects of foundry operations (Pare et al., 2018; Monteleone et al., 2024), a structured framework tailored to the unique characteristics and environmental implications of inorganic binder adoption in ferrous foundries remains underdeveloped. Monteleone et al. (2024) noted the limited number of studies collecting primary data from foundry plants and the lack of comprehensive comparisons across different binder systems. To address this gap, this study proposes a structured framework for LCA specifically designed for

the introduction of inorganic binders in ferrous foundries. Adhering to the guidelines outlined in ISO 14040 and drawing upon the recommendations of the ILCD framework, the developed model aims to enable a comprehensive assessment of environmental impacts throughout the entire production cycle. This includes a detailed consideration of: raw material acquisition and processing for both conventional and inorganic binders; the core blowing process and its associated energy and material inputs, energy consumption across all stages of the foundry operation; emissions to air, water, and soil resulting from the production process and the management of recovered materials and waste streams. Furthermore, the proposed framework integrates a comparative analysis between conventional production processes utilizing organic binders and innovative processes employing inorganic alternatives. This comparison will be supported by a synthesis of existing literature data. The aim of this research is to provide ferrous foundry companies with a quantitative tool that can inform strategic decision-making processes and facilitate the implementation of solutions that enhance the sustainability of their operations (Lanzini et al., 2024).

The expected outcomes of this study are anticipated to significantly contribute to the adoption of inorganic binders in ferrous foundries. By providing a robust and standardized LCA framework, this research will facilitate a more informed and data-driven transition within the industry towards lower environmental impact solutions, aligning with the growing global imperative for industrial sustainability. This is particularly relevant considering the potential of inorganic binders to offer environmental advantages over traditional organic binders by reducing the generation of hazardous substances during the casting process.

2. Context of the study

European foundries are undergoing a significant environmental transition following the publication of the new Best Available Techniques Reference Document (BREF) for the sector, which came into force in 2025. This document imposes stricter limits on air emissions, resource consumption and waste generation, incentivising the adoption of BAT. Among these, inorganic binders emerge as a promising solution to reduce harmful emissions in the foundry industry (Merta et al., 2021; Fratta et al., 2025). The foundry industry is fundamental to the economy, but it is also responsible for producing several potentially polluting and hazardous compounds (Vykoukal et al., 2019). The use of organic binders for the manufacture of sand cores and moulds is a major source of pollution, responsible to produce Polycyclic Aromatic Hydrocarbons (PAHs) and Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX) due to the thermal decomposition that the binders undergo when the molten metal is poured (Vykoukal et al., 2019; Merta et al., 2021). Despite inorganic binders proven environmental benefits and their increasing use in the production of non-ferrous metal castings, their application in ferrous foundries remains limited, mainly due to perceived economic and operational uncertainties for companies (Vykoukal et al.,

2019). Furthermore, there is still no strong consensus on the actual environmental benefits of implementing this new technological process. Several concerns have emerged, such as the potential increase in pollutants during core moulding or the challenges associated with recovering core sand after the casting has been removed from the mould. In line with ISO 14040 guidelines and the recommendations of the ILCD framework, the developed model enables the assessment of the environmental impact during the entire production cycle, considering raw materials, the core moulding process, energy consumption, emissions and the management of recovered materials (Mayanti et al., 2023; Ghormley et al., 2020; Yilmaz et al., 2015). The expected results will help bridge the current knowledge gap on the adoption of inorganic binders in ferrous foundries, facilitating the transition to solutions with a lower environmental impact.

3. Methods

This study aims to establish a clear and structured methodological approach for recording operational procedures and selecting the most appropriate methodology for environmental impact assessment. The developed standardized methodological framework aims to support and guide researchers in evaluating the implementation of inorganic binders in ferrous metal foundries by considering the various factors that influence resource consumption, emissions, and management of recovered materials.

A comprehensive literature review shows that the scope of environmental impact analysis and accessibility to relevant data vary significantly depending on the type of foundry and production processes involved. A literature review was conducted on March 9, 2025 using the Scopus database to identify original articles focused on the environmental impact of foundry processes.

The keywords identified were applied to title keywords and abstracts and are: ((foundry OR foundries OR "metal casting") AND ("life cycle assessment" OR lca OR "social and environmental life cycle assessment" OR "social and environmental life cycle analysis" OR selca OR s-elca OR lcsa OR "life cycle sustainability assessment" OR "life cycle sustainability analysis")).

The review process began with a preliminary selection, limiting the search to articles written in English and excluding, editorials, and letters. Then, after an initial screening of titles and a detailed review of abstracts, only open access articles were included, the full texts of which were obtained for further analysis.

Excluded studies were the ones that: 1) evaluated only environmental improvement initiatives without a structured quantification of the overall environmental impact; and 2) consisted of abstracts or conference proceedings without detailed data.

The final analysis included only studies quantifying the overall environmental impact associated with foundry processes.

Through the results of the literature review, a comprehensive methodological framework was proposed for a new LCA methodology adapted to the introduction of inorganic binders in iron foundries. This framework was developed to address gaps identified in previous studies by providing a more holistic and detailed assessment of environmental impact. The key element in improving the LCA framework is the identification of all steps in the production process with significant environmental impact. This allows the associated emissions to be more accurately calculated, providing a more accurate and comprehensive assessment of the overall environmental impact.

4. Results

The search resulted in 67 articles. After reviewing abstracts and full texts, including only those studies that structurally applied LCA to foundries and limiting ourselves to articles whose full text was available, the sample was reduced to 16 studies. The articles cover a time frame from 2004 to 2025.

4.1 Why is it important to do LCA in the foundry industry?

LCA analysis of a foundry is essential for multiple reasons related to both environmental sustainability and operational efficiency. Through this methodology, the overall environmental impact of the plant can be comprehensively assessed, considering energy and resource consumption, air and water emissions, and solid waste generation (Ghormley et al., 2020). In addition, this analytical approach allows for the identification of critical points, highlighting the production process steps or materials that have the greatest impact on environmental impact (Monteleone et al., 2024; Mayanti et al., 2023; Ghormley et al., 2020). Detailed knowledge of these impacts is the first step toward adopting more sustainable operational strategies (Yilmaz et al., 2015). Indeed, LCA provides a solid basis for developing cleaner production processes and establishing practices that reduce the overall environmental footprint. It also allows comparisons to be made between different smelters, smelting technologies or operating scenarios, facilitating benchmarking and adoption of BAT (Monteleone et al., 2024). An additional relevant aspect relates to strategic decision support (Zhu et al., 2023): data obtained from LCA provide valuable information for optimizing processes, choosing materials with lower environmental impact, and adopting more energy-efficient technologies. For example, replacing traditional energy sources with cleaner alternatives can lead to significant emission reductions (Chaurasiya et al., 2023).

In addition, LCA is internationally recognized under ISO 14040 and 14044 and plays a crucial role in ensuring compliance with environmental regulations (Monteleone et al., 2024).

Finally, the analysis of material and energy flows highlighted by LCA offers concrete insights to optimize production processes and reduce waste, promoting by-

product recycling and resource conservation (Cicconi et al., 2018). It is also an effective tool for tracking carbon footprint and promoting ecodesign, guiding design choices that, for example, by reducing the weight of castings, result in lower emissions and material consumption (Cicconi et al., 2018).

4.2 Processes included in system boundaries

To conduct an LCA study on the use of inorganic binders in foundries, the system boundaries should encompass the entire process chain, from material acquisition to waste treatment, structured into upstream, main, and downstream stages (Figure 1).

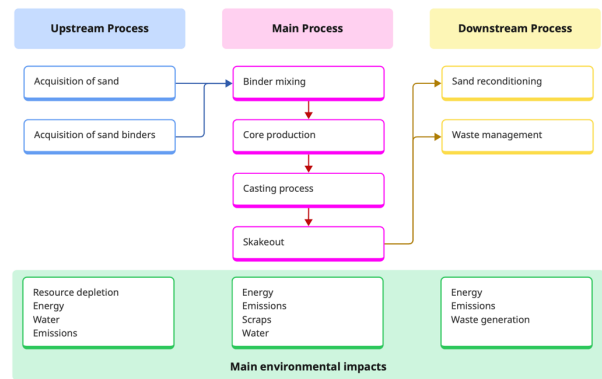


Figure 1: Upstream, main, and downstream stages of LCA

Upstream Process

This phase includes the Acquisition of sand and the Acquisition of sand binders, which are essential inputs for preparation in foundry operations using inorganic binders.

According to the literature, this stage involves: the extraction and processing of sand and raw materials used to produce inorganic binders, such as silica for sodium silicate (Gunasegaram et al., 2009); the preparation and handling of these materials prior to their use in the binder mixing phase (Mitterpach et al., 2017); transportation activities associated with these acquisitions must also be considered in the system boundaries (Astarita et al., 2023).

The main environmental impacts associated with the Upstream Process are: resource depletion due to the extraction of natural resources; energy consumption for processing and transport; water usage in material processing; emissions resulting from extraction, processing, and logistics activities.

Main Process

The main process of the analysis includes the foundry operations directly involving the use of inorganic binders.

Binder mixing. The process of preparing or mixing on site the inorganic binder with sand or other materials to form the mixture for cores and forms (Mitterpach et al., 2017).

Core production. This is the central stage in which inorganic binders are used to shape cores and molds (Mitterpach et al., 2017; Zhu et al., 2023).

Casting process. Although it does not involve the binder directly, the functionality and stability of the cores and molds (obtained due to the inorganic binder) during the casting of the molten metal are crucial and could be considered indirectly in the system (Zhu et al., 2023). During this phase it is very important to monitor emissions, because it is the contact between the core and the molten metal that results in the sublimation of the inorganic binders determined therefore emissions. Similarly, the temperature rise due to the contact with the molten metal determines the hardening of the inorganic cores impacting the next phase.

Shakeout. After solidification of the casting, it is separated from the mold and the cores are removed. The disintegration of the mold and cores held together by the inorganic binder and the resulting production of spent sand fall within the boundaries of the system (Mitterpach et al., 2017).

The main environmental impacts associated with the Main Process include: energy consumption across all stages, from mixing to shakeout; emissions produced by curing, thermal processes, and equipment; scraps, including defective parts and residual sand-binder mixtures; water usage, where applicable, in binder preparation or cooling systems.

Downstream Process

The final phase focuses on end-of-life treatment and circularity measures. Organic cores are more reclaimable because the process for making sand reclamation with organic binder is simpler and more standardized than inorganic.

Sand reconditioning. If the foundry adopts processes to recondition or regenerate sand bound with inorganic binders, these processes (e.g., screening, washing, heat treatment if necessary to remove specific residues of the inorganic binder) should be included.

Waste management. The management and disposal of the waste produced, including spent sand containing inorganic binder residues, filter dust, and other waste generated during the production of cores and molds and detaching (Monteleone et al., 2024).

The main environmental impacts associated with the Downstream Process include: energy consumption for regeneration equipment and waste processing; emissions resulting from thermal or mechanical treatment of waste and sand; waste generation, particularly in cases where regeneration is not possible or effective, leading to landfill disposal or incineration.

5. Discussion and limitation

In accordance with the study’s objectives, the definition of system boundaries is a critical step in ensuring the relevance and accuracy of LCA results, particularly when assessing the environmental impacts of inorganic binders (Astarita et al., 2023). Depending on the scope, one could take a cradle-to-gate approach, including the production of the raw materials for the binders, or a gate-to-gate approach, focusing on the processes occurring within the

foundry (Gunasegaram et al., 2009). A cradle-to-grave study would also include the use phase and final disposal of the casting, which may be less relevant if the focus is specifically on the inorganic binders within the foundry (Astarita et al., 2023). For a study focused specifically on inorganic binders, system boundaries would need to be precisely defined to capture all relevant processes related to their life cycle within the foundry, from the acquisition of constituent materials to the management of spent molds and cores. Consideration would also need to be given to whether to include the production of the binders themselves (from the cradle to the gate of the binder supplier supply chain) or just their use within the foundry (from gate to gate of foundry operations related to these binders). The choice will depend on the objectives of the study and the availability of data.

Beyond these methodological considerations, several practical challenges also emerge when applying the framework in real-world industrial contexts. A first obstacle concerns the granularity and completeness of environmental data: many foundries do not routinely monitor subprocesses such as binder mixing, core blowing, or sand regeneration with the level of detail required by LCA models. As a result, assessments often rely on averaged or proxy data, which may reduce the reliability of site-specific evaluations. Moreover, operational heterogeneity across foundries, in terms of scale, technologies, energy mix, and binder formulations, limits the possibility of producing generalizable results without appropriate adaptations.

Another key challenge lies in the operational usability of the framework. For the tool to support strategic decisions effectively, it must interface with existing production planning and environmental management systems, often requiring simplification or the integration of LCA outputs into more accessible performance indicators. The inclusion of upstream processes, such as the synthesis of sodium silicate or other binder components, adds complexity to boundary setting and may be constrained by limited supplier transparency or data availability.

Lastly, applying the framework often reveals trade-offs between environmental objectives: for example, reductions in volatile organic compound emissions during casting may be offset by increased electricity consumption for sand reclamation. These interdependencies highlight the need for a multi-criteria evaluation approach that can weigh benefits and burdens across impact categories. Addressing these challenges is essential to ensure the effective implementation of the framework and to support its broader adoption within the foundry sector.

6. Conclusion

This study developed a LCA framework designed to assess the environmental implications of introducing inorganic binders in ferrous foundries. The framework aligns with ISO 14040 principles and the ILCD recommendations, enabling comprehensive environmental evaluations across all key stages of the foundry process.

One of the key contributions of the framework lies in its ability to disaggregate impacts across subprocesses (e.g.,

binder preparation, core blowing, sand reclamation), thereby allowing the identification of environmental hotspots, defined as processes or inputs contributing disproportionately to the overall environmental burden. This capability enhances the interpretive power of the analysis and supports more informed mitigation strategies.

For illustrative purposes, the framework could be applied to compare two production scenarios within the same foundry: one employing conventional organic binders and another implementing inorganic binders. Modeling both scenarios using a common functional unit (e.g., 1 ton of castings) would reveal whether and where the environmental performance improves, for instance, by reducing volatile organic compound emissions during casting, but possibly increasing energy demand for sand reclamation. These insights provide quantitative support for decision-making and investment planning.

While the current implementation relies on a mix of primary and secondary data and is subject to uncertainty due to regional variability and data limitations, as highlighted in other foundry LCA studies (e.g., Monteleone et al., 2024; Herrera et al., 2022), the framework offers a replicable structure for future assessments. It contributes to filling a methodological gap in the literature by offering a binder-specific lens and lays the groundwork for integrating LCA into technology selection processes, especially under the evolving requirements of the BREF and BAT frameworks.

Future research should aim to expand the primary dataset, validate scenario-based assumptions, and test the framework in diverse industrial contexts. In this way, the tool can support broader adoption of cleaner technologies, facilitate compliance with regulatory standards, and guide foundries toward a more sustainable and data-informed transition.

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