Discrete Event Simulation Framework to assess the operational feasibility of inorganic cores in ferrous foundries

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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 toxic substances and pollutants, as well as resource consumption and waste production. One of the suggested BATs is represented by inorganic binders. However, while their use in the production of castings from non-ferrous metal alloys (such as aluminum) is increasingly widespread, the same cannot be said for the production of ferrous castings (iron and steel). The difficulties companies face in approaching the adoption of this new process arise from uncertainties regarding the feasibility of integrating this technology with the current industrial standard of organic cores. In the context of a foundry with an in-house core shop, an interesting gap emerges both from scientific literature and industry know-how, regarding structured methods to analyze the operational impact of introducing inorganic binders. This study aims to define a conceptual framework to support a simulation tool for future implementation. The underlying assumption is to maintain production output while analyzing the organizational impact of inorganic cores on the process. The objectives of this study are to propose a methodology based on Discrete Event Simulation (DES) principles, aimed at identifying the main variables, constraints, and decision levers associated with the reduced shelf life of inorganic cores. The proposed conceptual model can be used as a foundation for future quantitative simulations. Additionally, this study aims to bridge the gap in literature concerning the possibility of a hybrid adoption of this new technology in the foundry industry.

Keywords: DES, scenario analysis, Inorganic Binders, Ferrous Foundries, BREF.

1. Introduction and contextualization

The foundry industry is constantly evolving, driven by the need for more sustainable and high-performance processes. The adoption of inorganic binders in foundries is promoted by the European Union's Best Available Techniques (BAT), which aim to reduce emissions of volatile organic compounds (European Commission, 2024).

Cores are fundamental components in the foundry process, used to create cavities in steel and iron castings.

Inorganic binders are typically formulated from alkali silicates modified with inorganic additives such as phosphates or borates. Unlike organic binders, they are entirely carbon-free, meaning they do not contain hydrocarbon chains or aromatic compounds. As a result, during the core and mold burnout phase in the casting process, they do not produce harmful gaseous emissions such as volatile organics or polycyclic aromatic hydrocarbons. This intrinsic chemical property leads to a significant reduction in toxic emissions, lowers the need for post-casting ventilation and filtration systems, and improves both workplace safety and the overall environmental impact of the foundry (Izdebska-Szanda et al., 2013).

Historically, organic binders (phenolic resins, furans) have dominated the sector due to their long dimensional stability (shelf-life greater than 6 months), over 95% sand recovery through thermal regeneration, and compatibility with batch production logic. The introduction of inorganic binders changes these consolidated balances. It introduces significant operational and managerial challenges throughout the foundry’s production cycle (Vykoukal et al., 2019).

The accelerated perishability of the cores is the most immediate challenge. It reduces the shelf-life from several months to about 7 days, requiring a radical rethinking of production scheduling. This temporal limitation demands the implementation of just-in-time systems, with an increase in setup frequency and fragmentation of production batches, which must be sized based on daily consumption rather than economic optimization (Fratta and Saetta, 2025).

Sensitivity to ambient humidity is another operational issue. It requires strictly controlled climatic conditions in warehouses (30–50% relative humidity) to prevent premature degradation of the cores. This feature imposes investments in air conditioning and monitoring systems, as well as specific handling procedures to minimize exposure to humidity. The use of specific coatings becomes useful or necessary to protect the cores from hygroscopicity. This leads to additional costs both for materials and application equipment (Merta et al., 2021).

From an infrastructure perspective, inorganic binders require substantial modifications to existing equipment. They are used in the foundry process to produce sand cores and molds, which define internal cavities and surfaces of the final casting. Depending on their size and production volume, these cores can be manufactured either manually or using machines known as core shooters. These machines use compressed air to inject a sand and binder mixture into metal molds, called core boxes, shaped according to the desired geometry. The mixture is then hardened either by applying heat or through chemical reactions, depending on the production method.

Most foundries currently using core shooters adopt a process known as cold box, which involves gaseous chemical catalysts to cure the mixture at room temperature. However, unlike the organic ones, many inorganic binder technologies require elevated temperatures for proper curing, making it necessary to replace traditional core molds and boxes with heat-resistant alternatives. As a consequence, core boxes previously made of aluminum need to be made of steel, due to the higher thermal and mechanical stress. This change increases production complexity and cost, as steel is more difficult to machine than aluminum and requires longer processing times.

Operational difficulties also extend to the core removal phase. The increase in mechanical strength of inorganic binders hinders the removal of cores after casting. This phenomenon requires additional cleaning and finishing operations, increasing cycle times and labor costs (Fratta et al., 2024).

Despite these issues, inorganic binders provide substantial benefits in terms of enhancing working conditions and reducing pollutant emissions (European Commission, 2024).

The introduction of inorganic binder cores in the ferrous foundry sector is still under study and experimentation. Existing literature focuses mainly on the chemical-physical aspects and characterization of this new product, with specific attention to laboratory evaluations of mechanical properties (Mantelli, 2022). Thus, there is a gap regarding the study of possible applications in real operational and production contexts.

Having identified the main operational and production challenge, namely the drastic reduction in core shelf-life and the resulting need to modify batch management logic, this work aims to present a methodological approach based on Discrete Event Simulation (DES) to answer the research question: "How and to what extent does the reduced shelf-life of inorganic binder cores impact the organization of the production system?"

The motivation for using DES lies in the fact that scenario analysis is one of the traditional application areas of simulation. The purpose of the simulator is to evaluate different levels of technological adoption, progressively introducing changes in both batch sizing logic and production organization. The next section presents the method. Section 3 presents the conceptual model. Section 4 presents expected results and discussion. The conclusions will follow.

2. Method

Discrete Event Simulation (DES) represents the standard methodology for modeling complex production systems, characterized by discrete state changes and dynamic interactions between resources. This approach allows for the representation of process stochasticity, testing of alternative scenarios, and identification of criticalities not evident through static analysis. In this case, DES enables the evaluation of the impact of reduced core shelf-life and comparison of different production and inventory management strategies. In particular, it allows the quantification of waste due to perishability, the testing of adaptive lot-sizing policies, namely different strategies to adjust the order quantity for core storage, and different management approaches for finished product orders.

The methodological approach adopted in this study is structured into three main phases. Each phase is designed to ensure a functional representation of the production reality under study.

The starting point is the detailed mapping of the production process. Particular attention has been paid to material flows and interactions between different functional areas. A specific focus was placed on core management. Critical points were identified, emerging from the introduction of inorganic binders, such as the management of the intermediate core warehouse and the need to synchronize core production with molten steel casting on the casting line.

Subsequently, the process has been formalized through the development of a conceptual model. This model allows for a structured representation of relevant events in the production chain, both in a deterministic and a stochastic environment. The event graph focuses on the aspects most affected by core shelf-life. Emphasis is given to modeling critical events related to core perishability, rebatching operations, and operational constraints imposed by the reduced shelf-life. External logistics or specific technicalities of the melting process have been excluded from modeling.

Finally, the conceptual model will be translated into a discrete event simulator. This simulator will generate and manage events according to the operational logic identified in the analysis phase. It enables the exploration of different management scenarios through "what-if" simulations and the quantification of the strategic choices' impact on overall system performance. The objective is to provide a comprehensive overview of possible operational configurations. It highlights cause-effect relationships among the critical process variables.

3. Conceptual model

The starting point for building the conceptual model was the typical production process of a ferrous foundry, which has been mapped in detail. The cycle begins with the melting of metal in dedicated furnaces. The molten metal is then poured into ladles. Each ladle contains enough metal to cast a limited number of parts. For this reason, multiple ladles are needed to complete a single batch. Once at the casting line, the metal is poured into molds, inside which the cores have already been positioned. After casting, the parts are cooled before being extracted and subjected to subsequent phases such as core removal, cleaning, and possible finishing.

The molds are made of flasks in which the cores are placed in advance. These cores are produced in-house through a multi-phase process. The first is the blowing process, carried out in a dedicated department using core shooting machines of different sizes and capacities, selected based on the mass of the core to be produced. Each mold can produce variable number of sets of cores, depending on the geometry and size of the flask.

After blowing, the cores undergo a coating phase. The coating time of each sub-batch depends significantly on the shape and weight of the core. For particularly complex geometries, the coating phase can be a critical moment and may require manual operations to ensure the integrity of the cores.

Next, the coated cores are sent to the drying phase, which takes place inside an oven. The oven is sized to host a finite number of transport units, each of which can hold a certain number of cores depending on their size and weight.

To efficiently manage transfers and capacity differences between blowing, coating, and drying, the initial batch of cores is divided into sub-batches through a rebatching process, immediately after blowing. This allows the adaptation of the flows to the capacity and the time constraints of each phase. Once the cores are completed, the sub-batches are reassembled in the warehouse, where they are stored until used on the casting line.

The key dimensions are therefore:

- Q: Product type;
- A: Core type;
- B: Blowing phase;
- B_h: Blowing machine;
- P: Painting stage (single machine);
- D: Drying stage (single machine);
- W: Storage stage;
- C: Casting stage (single line);
- i: Core type index;
- j: Binder type index;
- k: Product type index;
- h: Blowing machine index;
- z: Process stage $z = \{B, P, D, W, C\}$;
- A'_{ijkz}: Batch after rebatching;
- x_i: Units of core i per handling system;
- s_i: Units of core i per ladle;
- r_i: Characteristic transformation ratio for each core type;
- T_a: Interarrival time of orders;
- T_{hij}: Blowing time per machine h, core i, binder j;
- T^P_{ij}: Coating time per core i, binder j;
- T^D_{ij}: Drying time per core i, binder j;
- T^{SU}_{ij}: Casting line setup time;
- T_{change}: Ladle replacement time.

In the conceptual model, presented as an event graph (Appendix A), the only represented elements of the production process are the ones potentially influenced by the reduced shelf-life of the cores. The aim is to focus on the operational dynamics that may be affected by perishability, particularly in the consolidation phase in the warehouse that precedes feeding the casting line.

The limited shelf-life can generate significant effects on warehouse occupancy, on the management of usage priorities, and, in the worst cases, result in the disposal of cores no longer suitable for use. Thus, the model focuses on events directly involved in these criticalities.

The relevant events and transitions are reported in the graph, where the changes of the main state variables are traced. Each node in the graph represents an event associated with production phases, while the arcs indicate causal relationships and time flows between activities. The variables involved are dynamically updated at key events.

The relationships in this model will form the basis for implementing the discrete event simulator and will undergo a phase of qualitative and quantitative validation (Lanzini et al., 2024). After validation, it will be possible to analyze a set of different scenarios in order to distinctly and thoroughly evaluate the operational implications of: the technology change; the effects of batch sizing logic modifications; and the changes in order organization on the system.

The conceptual model relies on a set of assumptions aimed at capturing the core dynamics of the system. It is assumed that the overall production demand remains constant across all simulated scenarios, so that changes in performance can be directly attributed to managerial decisions. Core manufacturing is assumed to be fully internalized, excluding any contribution from external suppliers. The model includes a single casting line and focuses only on the stages directly affected by the reduced shelf-life of inorganic cores. Melting operations, external logistics, and environmental regulations are excluded from the scope of the analysis.

Shelf-life can be modeled both as a stochastic or a deterministic constraint, and cores that exceed the assigned storage time are discarded, with no possibility of reprocessing. The core production flow includes batch splitting and reassembly steps to reflect real operational constraints, particularly in the coating and drying phases. Energy consumption and emission outputs are not represented, although the emissions can be evaluated, even if they will not be a decision variable or a control parameter. Finally, the model includes stochastic variability in processing times and shelf-life.

The expected results and discussion will follow in the next section.

4. Expected results and discussion

This section describes the simulation strategy and scenario management plan, with the aim of highlighting the objectives of the analysis and the decision-making purposes being pursued.

The simulation plan includes the analysis of 15 scenarios, obtained by combining different levels of penetration of inorganic binders (from 20% to 100%) with three operational strategies, as shown in Appendix B. The reference "AS IS" scenario corresponds to the case with 0% technological substitution, in which the batch sizing and order management logics are those currently in use.

The operational strategies considered are the following:

- Current logic: production based on predefined economic batches, not adjusted for the reduced shelf-life. The order management logics are those currently adopted by the company;
- Corrected batch size: recalculation of the order quantities considering the temporal constraint of core perishability. The order management logics remain those currently used by the company;
- Corrected batch size and new order management: in addition to order quantities adaptation to the time constraint, a reorganization of production scheduling is introduced, with various strategies aimed at aligning core production with the casting line output.

In the literature, several strategies are proposed to correct batch sizes in the presence of perishability constraints (Silver et al., 2016). The choice depends on the operational and managerial characteristics of the system considered (Karaesmen et al., 2011). For example, in contexts with stable demand and reliable lead times, it is possible to introduce a rigid constraint on the maximum batch size based on shelf-life. In more complex scenarios, where reliable estimates of product decay rate are available, perishability can be modeled as deterministic loss and integrated into the cost function.

At present, no single optimal approach has been identified that applies in all cases. Therefore, depending on the production system and the level of adoption of inorganic binders, multiple lot sizing adaptation methods may coexist, each better suited to specific operational conditions. Examples of such strategies include fixed-lifetime lot sizing, perishability-aware EOQ extensions, and just-in-time approaches synchronized with casting operations (Berk et al. 2020).

In addition to lot size adaptation, it is possible to intervene in the order management strategies of finished products in order to better align the timing of core use and casting line production. By appropriately modifying the release and sequencing policies of orders, it is possible to reduce core storage time and limit the risk of disposal due to shelf-life expiration. Among the possible strategies there are: grouping orders by core type, planning with fixed time windows (time buckets), and synchronous scheduling between core production and casting, in a just-in-time logic. These techniques aim to ensure better coherence between demand and core availability, improving the robustness of the production system under perishability constraints.

The model results focus on these quantitative measures:

- warehouse occupancy;
- waste due to shelf-life expiration;
- overall department effectiveness (OEE);
- level of emissions produced.

These indicators allow for an objective assessment of the impact of the different simulated strategies and for comparing results in terms of operational and environmental performance.

The objective of the analysis is to understand how management choices, particularly lot sizing modification and scheduling reorganization, directly affect these metrics. In general, total costs are expected to increase with the substitution of traditional cores with inorganic binder ones. This applies to all simulated categories. At the same time, the expectation is that higher substitution rates will lead to a progressive reduction in pollutant emissions. The main point of interest in the analysis will be the identification of the most effective strategies and management techniques to ensure good performance in the observed quantitative parameters while containing costs.

Based on the scenario structure and the identified managerial levers, it is expected that different operational contexts will require distinct combinations of batch sizing and scheduling policies. In settings where the adoption of inorganic binders introduces significant constraints due to core perishability, it is expected that small and frequent batches, together with just-in-time synchronization with the casting line, will be necessary to avoid waste. In more balanced situations, medium-sized batches are expected to be sufficient to ensure coordination and resource efficiency. Conversely, in more stable or traditional contexts, standard batch sizing and current scheduling policies will likely remain viable, as the impact of core degradation would be limited.

It is also expected that systems characterized by a high degree of product mix complexity will benefit from modular batch structures organized by core type, facilitating alignment between core production and mold assembly. When storage capacity is limited or climate control is not available, minimizing inventory levels and ensuring immediate consumption of cores after production are expected to be the most effective strategies to reduce the risk of spoilage. In environments subject to high demand variability, adaptive batch sizing and rolling-horizon planning are expected to offer the necessary flexibility to maintain system responsiveness under changing operating conditions.

Conclusions

This work addressed the issue of replacing traditional cores with inorganic binder cores in ferrous foundry processes, highlighting the operational and managerial challenges related to the drastic reduction in core shelf-life. Through the implementation of a DES framework, a methodology was proposed to analyze the impact of the new technology on production management. The approach allows for the identification of critical areas within the production system and for the structuring of what-if scenarios to evaluate alternative strategies, such as lot sizing adaptation and order management reorganization. The purpose is to provide a decision-support tool for planning the technological transition in line with BAT directives and environmental sustainability goals.

Among the main limitations of the conceptual model are the absence of an explicit representation of furnace management, energy consumption, and environmental constraints related to waste limits. Future developments will include the implementation of the simulator, quantitative analysis of the identified scenarios, and the progressive integration of energy, environmental, and production variables. (Leoni et al., 2021; Worrell et al., 2010; Leggerini and Bannò, 2025)

Additional extensions will include real-time decision-making logic, supported by optimization tools and digital twin paradigms (Lanzini et al., 2023; 2024).

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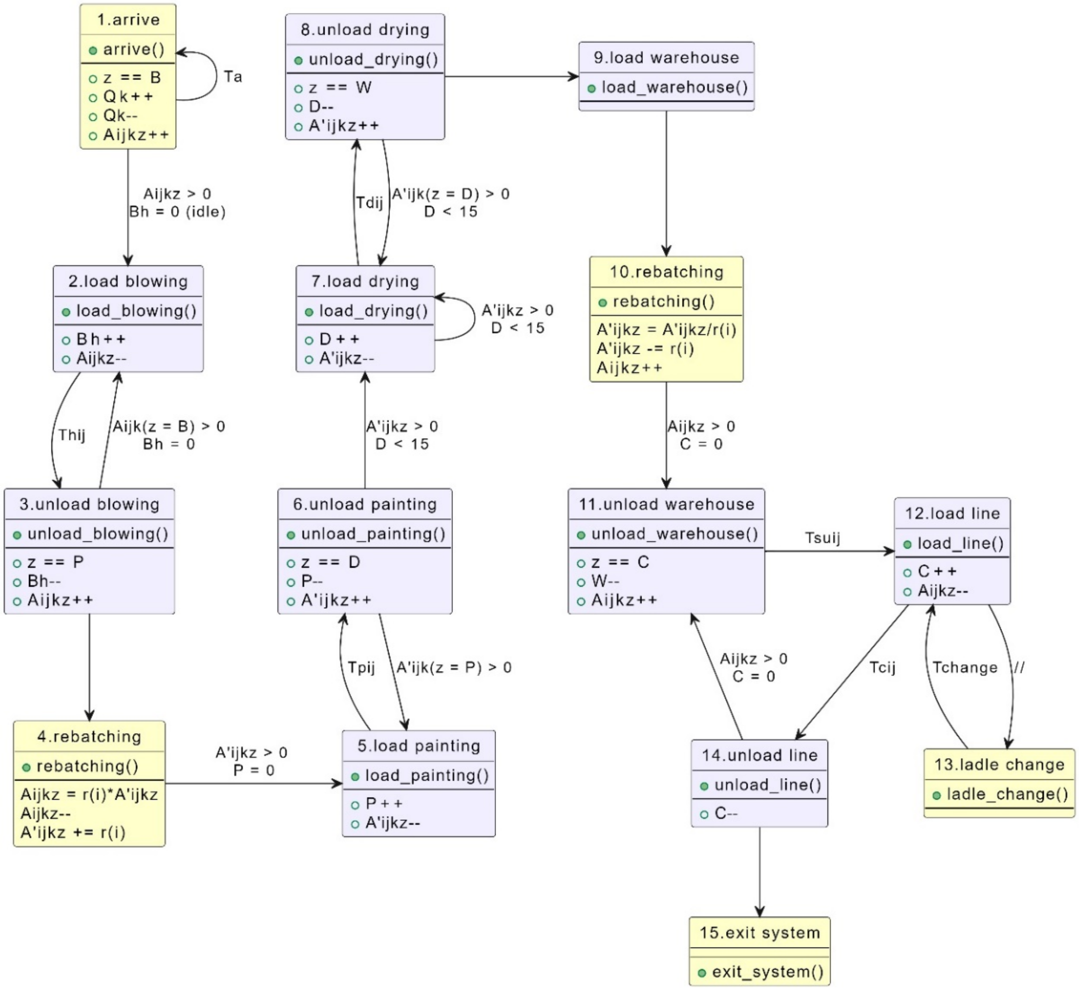
Appendix A. Event graph for the modelled process



Appendix B. Scenario representation table

% cores with inorganic binders vs strategy employed	0%	20%	40%	60%	80%	100%
Current logic	AS IS	Scenarios 1-5				
Lot size correction	-	Scenarios 6-10				
Lot size correction and new order management	-	Scenarios 11-15				