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Criticality-Driven Reliability Enhancement of Pneumatic Sand Molding Cells in Foundry Applications via FMECA

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Abstract: In modern foundry operations, the reliability and operational continuity of sand molding systems are pivotal to maintaining productivity, safety, and competitive advantage. In this study, Failure Mode, Effects, and Criticality Analysis (FMECA) has been employed to systematically evaluate and optimize the performance of a pneumatic molding cell utilized in the production of sand molds. Particular focus has been directed toward the pusher subsystem, which is frequently subjected to high mechanical loads and cyclic stress, rendering it susceptible to recurrent failures that compromise both uptime and process efficiency. Potential failure modes were exhaustively identified, categorized, and prioritized based on their severity, occurrence, and detectability. Critical components, including servo motors, pneumatic actuators, and gearbox assemblies, were found to pose substantial risk to system reliability due to wear-induced degradation, misalignment, and lubrication failure. For each high-priority failure mode, targeted mitigation strategies were proposed, encompassing enhanced condition monitoring, retrofitting of wear-resistant materials, and redesign of high-stress interfaces. Furthermore, failure detection mechanisms were improved through the integration of predictive maintenance protocols and sensor-based diagnostics. Implementation of these recommendations has resulted in measurable reductions in unplanned downtime, repair frequency, and maintenance overhead. This investigation demonstrates that FMECA, though underutilized in conventional foundry environments, offers a structured, data-driven methodology for uncovering latent failure risks and implementing preventive measures in complex industrial systems. By embedding FMECA within routine maintenance frameworks, a substantial improvement in operational resilience and equipment lifespan can be achieved. The findings support the strategic integration of reliability engineering methodologies into sand molding operations, contributing not only to cost efficiency but also to the broader adoption of systematic risk management practices in process-driven manufacturing sectors.

Keywords: Failure Mode, Effects, and Criticality Analysis (FMECA); Foundry engineering; Pneumatic sand molding; Reliability optimization; Industrial risk assessment; Mechanical failure analysis; Predictive maintenance; Operational resilience

1 Introduction

In the continuously evolving landscape of the foundry industry, the need for reliable and efficient processes is paramount to maintaining competitiveness and ensuring operational safety. Foundries, which are pivotal in shaping the components fundamental to various sectors such as automotive, construction, and aerospace, face the ongoing challenge of optimizing their processes while mitigating risks associated with equipment failure and system inefficiencies [1]. In foundry operations, the molding system is a key area of concern, where even minor deviations in equipment performance can significantly compromise product quality and reduce production throughput [2].

The methodology of FMECA presents a structured approach to identify and systematically address potential failures in complex systems. FMECA is a powerful and widely used method for analyzing the reliability of complex systems, allowing the identification, classification, and prioritization of potential failure modes based on their impact on system performance [3].

Although widely recognized in industries such as aerospace [4, 5] and automotive [6–8] for its efficacy in improving safety and reliability [4–8], FMECA has not been as prevalently adopted in the foundry sector, although relevant experiences already exist [9–11].

This discrepancy can be attributed to various factors, including the unique operational challenges and the traditional reliance on empirical methods within the foundry industry.

Given the high complexity and interconnectivity of operations in modern foundries, a systemic approach to process management, maintenance, and data analysis proves to be particularly effective. From the coordination of production flows to the implementation of reliability-centred maintenance strategies and data-driven monitoring of molding systems, numerous studies have demonstrated the value of structured methodologies in enhancing quality, minimizing downtime, and improving overall operational efficiency [12–15].

This paper explores the application of FMECA to a green sand molding system in a medium-sized foundry, aiming to highlight how this method can be instrumental in transforming foundry operations. The sand molding process, characterized by its intense mechanical and operational demands, exposes equipment like the pusher system to significant wear and tear, making it susceptible to critical failures that can severely impact production efficiency and safety.

By integrating FMECA, the study seeks to achieve a dual objective: firstly, to conduct a critical evaluation of the molding system, identifying potential failure modes and their effects on the foundry's operations; and secondly, to develop and implement corrective actions that enhance the overall reliability and efficiency of the process. The focus on the pusher system, a crucial component of the sand molding line, provides a detailed examination of the risks associated with one of the most strenuous aspects of foundry operations.

Through a comprehensive review of existing literature on FMECA applications in similar industrial settings, combined with a systematic analysis of the foundry's current operational challenges, this paper aims to contribute significantly to the literature on industrial process optimization. It also addresses the gap in research regarding the application of advanced risk assessment techniques in the foundry industry, proposing a model that can be replicated or adapted for similar challenges in other sectors.

In doing so, this study not only underscores the importance of adopting systematic and analytical approaches like FMECA in traditional manufacturing environments but also demonstrates the tangible benefits of such methodologies in enhancing operational reliability, reducing downtime, and optimizing cost-efficiency. Thus, the paper sets the stage for a broader discussion on the strategic integration of risk management tools in the foundry industry, paving the way for more resilient and competitive manufacturing practices.

2 Methodology

2.1 FMECA

FMECA is a very well-known methodology [16] that here helped to:

- Identify failure modes of systems and sub-components.
- Evaluate the effects of each failure on safety, production efficiency and product quality.
- Combine all the information toward an effective corrective strategy to mitigate the most critical risks.

According to its scope, it allowed answering questions like:

- "How can this process or system fail?"
- "What effect will it have if a certain failure mode occurs?"
- "What actions can be taken to prevent this risk?"

The analysis was carried out on each individual component or subsystem and aimed to predict the onset of any problem at any time during the system's life by checking whether there are expected conditions under which the component could become critical and observing each time the possible consequences on the system (bottom-up technique) with particular attention to dangerous situations.

FMECA was used to make corrections on each individual subsystem, ensuring that:

- all failure modes and their consequences were considered and that these have been, where possible, contained or eliminated.
- information was produced in design reviews for maintainability analysis and for quantitative analysis of product reliability and safety availability.

To proceed with the examination of failures and their effects, the following path was followed:
1. Identify the entire system.
2. Identify each component, each subsystem, and each group.
3. List every way in which each identified element can fail.
4. Evaluate how the problem appears to the user.
5. Determine what effects failures may have on the product, environment and users.
6. Classify each effect by severity of consequences.
7. Describe the protections.
8. Estimate and classify the probabilities of failure.
9. Define and classify the possibility of early detection of failure.
10. Compare the probability, severity and possibility of early detection of the failure.
11. Establish the procedures (from design review to warnings for use).

From a strictly operational point of view, FMECA was implemented as follows:
- define the expectations, the implementation methodology and the responsibilities of the analysis.
- define process phases and layout documentation.
- group all potential failure modes (potential failure modes).
- discuss and define the effects (failure effects) on the process.
- detect and define the causes (failure causes) generating the failure mode.
- discuss and define the methods of failure identification and evaluation.
- assess and quantify the severity on the system of such failure mode (severity).
- evaluate and quantify the probability of occurrence of each cause of failure (probability).
- evaluate and quantify the probability that control systems have of detecting the failure (occurrence).
- define a methodology for comparing the severity of different failure modes.
- sort potential failure modes by severity.
- develop a strategy that reduces the effect and/or cause of the most severe failure modes.
- assess how corrective actions impact the relative failure mode.
- repeat the comparison and correction operations until the desired level of reliability is achieved.

2.2 Empirical Scales

To quantify the quantities involved, empirical scales were defined and used. Specifically:

1. The severity (S) associated with a failure mode means the risk that that particular failure mode would cause to the system if it were to manifest itself, indicating with 1 that failure mode that would not imply any form of malfunction of the complete system (relative to those malfunctions on which the attention of the particular FMECA in question is concentrated) and with 10 those modes that involve damage of maximum criticality to the system (Table 1).

Table 1. Empirical scale for evaluating the severity of failure effects on system functionality and safety

Severity	Index	Criterion
Dangerous	10	Immediate danger to personnel or major violation of safety regulations
Serious	9	Severe damage to system; potential safety concern; process shutdown likely
Extreme	8	System non-functional; complete production halt, but no safety issues
Greater	7	Severe degradation of system performance; frequent downtime
Significant	6	Noticeable impact on production efficiency; reduced output
Moderate	5	Partial loss of functionality; minor rework or delay required
Minor	4	Slight degradation of performance; process continues
Mild	3	Negligible effect on operation; easily corrected
Very mild	2	No real effect on performance; no action required
Nobody	1	No impact on system or process

2. The recurrence (R) refers to the probability of occurrence of the said cause by associating 1 to those causes that have a reasonably negligible probability of occurring and 10 to those causes that are practically certain to occur (Table 2).

Table 2. Empirical scale for estimating the probability of occurrence of failure causes

Recurrence	Index	Defects	Criterion
Almost certain	10	$>$ 1 out of 2	Defect that almost certainly manifests itself
Very high	9	1 in 3	Very high number of probable defects
High	8	1 in 8	High number of probable defects
Medium high	7	1 in 20	Number of probable defects medium high
Medium	6	1 in 80	Number of defects within the average
Bass	5	1 in 400	Moderate number of defects
Mild	4	1 in 2000	Occasional defects, but worthy of attention
Very mild	3	1 in 15,000	Occasional and sporadic defects
Remote	2	1 in 150,000	Remote possibility of defects appearing
Nobody	1	1 in 1,500,000	No chance of defects appearing

3. The detectability (D) refers to the efficiency of process control systems in detecting a possible malfunction in the process, preventing the failure effects from occurring. Detectability is expressed on a semi-empirical scale with extremes of 0-10, with 1 indicating those defects that have no reasonable probability of passing the control systems (i.e., high detectability), and 10 indicating those malfunctions that cannot be detected by current verification systems, i.e., low detectability (Table 3).

Table 3. Empirical scale for assessing the probability of detecting failure modes before their effects occur

Detectability	Index	Detection Probability	Criterion
Almost certain	10	1 out of 2	No possibility to detect defects
Very high	9	1 in 3	Remote ability to detect defects
High	8	1 in 8	Inefficient detection systems
Moderate high	7	1 in 20	Poor detection, random checks
Medium	6	1 in 80	Low detection, partial sample limits
Bass	5	1 in 400	Low detection, partial random limits
Mild	4	1 in 2,000	Medium-efficient detection systems
Very mild	3	1 in 15,000	Highly efficient detection systems
Remote	2	1 in 150,000	Extremely efficient detection systems
Almost impossible	1	1 in 1,500,000	All defects are detected

Although technical literature offers comparative tables to guide the definition of empirical severity, occurrence, and detection scales, their effective use must be critically assessed in the context of the specific process under analysis. In process FMECA, the frequency of a failure mode cannot be interpreted in absolute terms, but rather in relation to the production volumes, cycle times, and system redundancy. For instance, a failure with a theoretical occurrence of one in a thousand cycles may be negligible in low-volume batch production, but becomes critical in high-throughput continuous operations where thousands of cycles occur within short timeframes. Therefore, maintaining internal consistency in the application of scoring criteria is crucial to ensure a realistic and balanced risk assessment.

2.3 Ranking

Starting from these empirical scales, it was possible to define a Risk Priority Number (RPN), which standardizes different failure modes and their causes, allowing for effective comparison and prioritization. The RPN highlights the main risk contributors and provides a clear basis for ranking corrective actions. It is typically calculated as follows:

$$RPN = S \times R \times D \tag{1}$$

where, S = Severity Index, R = Recurrence Index and D = Detectability Index.

The risk index RPN was evaluated with respect to each failure mode/failure cause combination, and a risk scale was achieved to define the intervention priorities.

The intervention generally consisted in choosing a remedy that allowed at least one of the following outcomes:

- Reducing the probability of occurrence of failure causes, thereby lowering the Recurrence index (R) (e.g., by modifying the process or selecting more robust components).

- Increasing the probability of detection before the failure effect occurs, thus improving the Detectability index (D) (e.g., by implementing additional or more effective control systems).

Although it is generally advisable to act simultaneously on both coefficients to rapidly lower the risk index, this operation can often prove to be complex or expensive. However, by observing the values of the indices, it is possible to have an indication of where it would be advisable to intervene. For example, it could be easier to decrease the detectability index by many points by improving the control system rather than redesigning the component and/or process by trying to lower the severity even by just one point. Finally, while severity represents the intrinsic impact of a failure once it occurs, and is therefore not directly modifiable, it may only be influenced through substantial redesigns that alter the nature or consequences of the failure itself. In the FMECA context, severity remains constant unless the system is fundamentally changed to mitigate the effect.

2.4 Foundry (System)

The sand-casting foundry analyzed in this study, owned by SCM Group Spa and located in Italy, constitutes a complex industrial system designed to transform molten metal alloys into solid components through casting into sand molds [17].

Numerous scientific studies have been carried out within this facility, which is frequently used for research purposes. Among the most significant contributions are the characterization of ferrous materials - particularly grey and ductile cast irons - the application of artificial intelligence techniques, as well as the development and optimization of non-traditional materials such as compacted graphite iron [18–20].

The entire production process is structured into a series of interconnected subsystems, each performing a specific function within the overall workflow. Key systems include the following (Figure 1 and Figure 2):

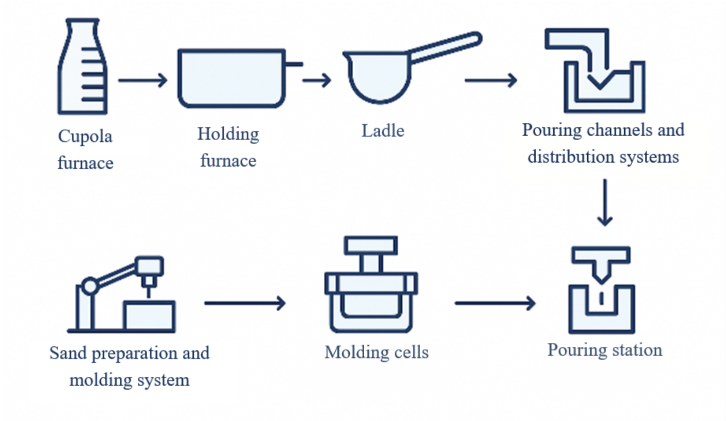


Figure 1. Representation of the sand-cast foundry in main sub-systems

(a) (b) (c)

Figure 2. (a) Pouring channel; (b) holding furnace; (c) ladle

- Cupola furnace: the primary system used to melt metal, commonly employed for cast iron or non-ferrous alloys. The cupola enables continuous melting with layered charging of metal, coke, and fluxes.

- Holding furnace: used to maintain the molten metal at the correct casting temperature, preventing premature cooling and solidification.

- Pouring channels and distribution systems: pre-formed structures that guide the molten metal from the pouring station (e.g., from the ladle) into mold cavities.

- Ladle: a mobile, refractory-lined container used to transport molten metal from the furnace to the pouring station. It can be moved manually, mechanically, or via overhead crane systems.

- Sand preparation and molding system: includes silica sand, bentonite, water, and additives to produce molds that are both resistant and collapsible, following the sand process.

- Molding cell: operational unit that compacts the sand inside the flasks, ensuring accurate shape reproduction of the final casting. These systems may be mechanical, hydraulic, or pneumatic.

- Shake-out and mold stripping systems: once the casting has solidified, these systems remove the sand and extract the part from the mold.

- Sand reclamation plant: a system designed to recover, cool, screen, and rehydrate used sand, making it suitable for reuse in the molding process.

2.5 Molding Cell (Subsystem)

Within this production framework, the molding cell under investigation represents a critical sub-system for the precision and efficiency of the molding process. It is an automated unit specifically designed to produce sand molds through pneumatic compaction, by a filling-compression-release sequence (Figure 3), using compressed air to apply uniform pressure to the sand within the flasks by the following operational sequence (in subgraph (a) of Figure 4):

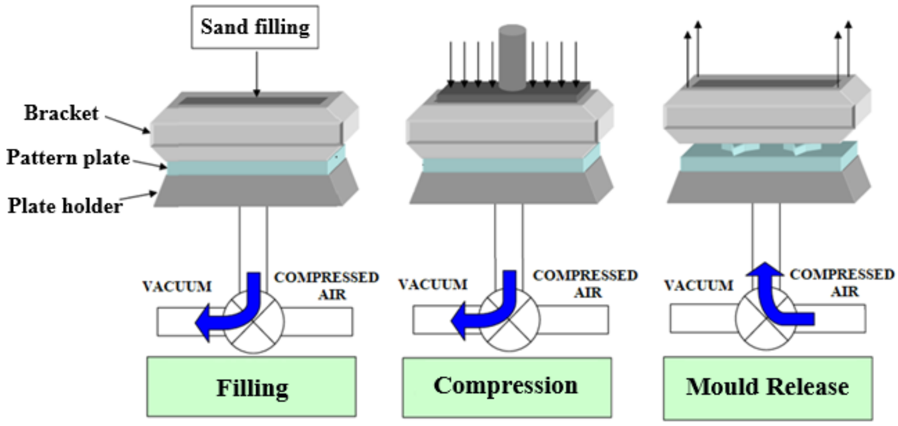
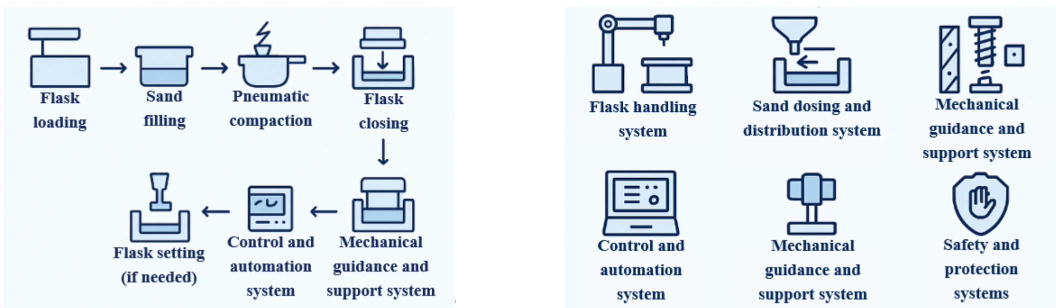


Figure 3. Operating phases of the sand forming process



(a) (b)

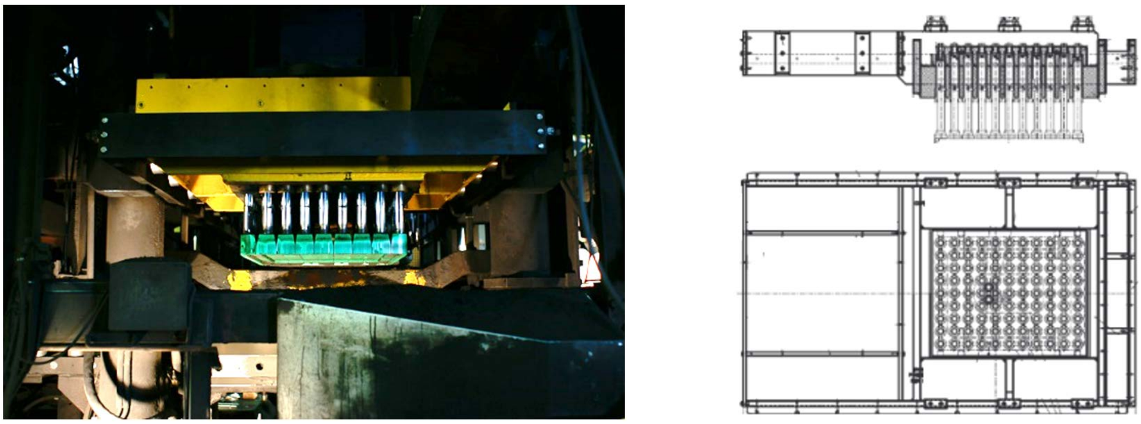
Figure 4. Representation of the (a) pneumatic molding cell and (b) main functional units

- Flask loading: an empty flask (either cope or drag) is positioned at the molding station.
- Sand filling: a dosing system releases the pre-measured quantity of green sand into the flask.
- Pneumatic compaction: a compressed-air-driven piston presses the sand into the flask, ensuring the required density and shape.
- Core setting (if needed): a core is inserted to form internal cavities in the final casting.
- Flask closing: cope and drag are aligned and joined, completing the mold assembly.

And the following main functional units (in subgraph (b) of Figure 4):

1. Flask handling system: often servo-driven, it enables the precise and automated transport of the flasks between the various stations (filling, compaction, extraction).
2. Sand dosing and distribution system: ensures the correct amount and uniform distribution of sand within the flask.
3. Pneumatic compaction unit: the core of the cell, it utilizes compressed air pistons to apply controlled pressure to the sand.
4. Control and automation system: PLCs, position sensors, limit switches, regulating every phase of the operating cycle.
5. Mechanical guidance and support system: including roller guides, threaded fasteners, compensation springs, and structural frames to ensure stability, precision, and durability.
6. Safety and protection systems: physical barriers, interlocks, and sensors safeguard operators and critical components throughout the process.

In this study, FMECA was applied in an extended and systematic way, with the objective of identifying potential failure risks across multiple functional units of a pneumatic molding cell (in subgraph (a) of Figure 5) including:



(a) (b)

Figure 5. Sand molding cell with the rammer head assembly: (a) real-life view; (b) technical drawing

(a) The rammer head assembly, a complex structural unit equipped with 120 independent pistons (rammers) driven by three separate hydraulic circuits (in subgraph (b) of Figure 5). This assembly plays a fundamental role in achieving proper sand compaction within the flask, a key requirement for ensuring the dimensional accuracy and surface integrity of the final casting. The rammers are actuated based on feedback-controlled PLC logic and are distributed over a heated pattern plate that interfaces with the sand mold. Failures in this unit can lead to insufficient compaction, voids, or defects in the casting, making it one of the most critical components in the cell.

(b) The crank-slider translation mechanism, also referred to as the biella-manovella system, enables the controlled horizontal movement of the rammer head. This motion is essential to position the rammer assembly above the flask in preparation for compaction. The mechanism includes a combination of bearings, mechanical joints, and a flywheel system that converts rotational motion into linear displacement. Mechanical wear, alignment issues, or lubrication failures in this mechanism can cause inaccurate positioning or reduced operational repeatability, compromising the entire forming cycle.

(c) The servo-actuated bracket pusher unit, which is responsible for transferring the flasks between different stations within the molding cell, such as sand filling, compaction, core setting, and mold closing. This unit is driven by a brushless AC servomotor, connected via an elastic coupling to an orthogonal-axis reduction gearbox, and employs a rack-and-pinion transmission to convert rotary into linear motion. The pusher is mounted on a guided system with axial rollers and limit switches that define the stroke range. Its reliability is crucial for maintaining production rhythm and synchronization across stations. Issues such as backlash, sensor misalignment, or motor overheating can lead to cycle interruptions and increased downtime.

Each subsystem was subjected to a detailed functional decomposition, followed by the development of component-to-function correlation matrices, and subsequently evaluated through FMECA. Where relevant, a Fault Tree Analysis (FTA) was also performed to trace critical failure paths and quantify the impact of combined faults. The level of detail varied slightly across the components, with the rammer head and crank-slider mechanism receiving an especially deep analysis due to their mechanical complexity and number of interacting elements.

The present paper focuses specifically on the servo-actuated bracket pusher unit, which, while mechanically simpler than other components, plays a pivotal role in the coordination and continuity of the molding process. The unit's failure modes, critical components, and improvement strategies are discussed in detail, offering a representative case study of how FMECA can be effectively applied to optimize reliability in foundry automation systems.

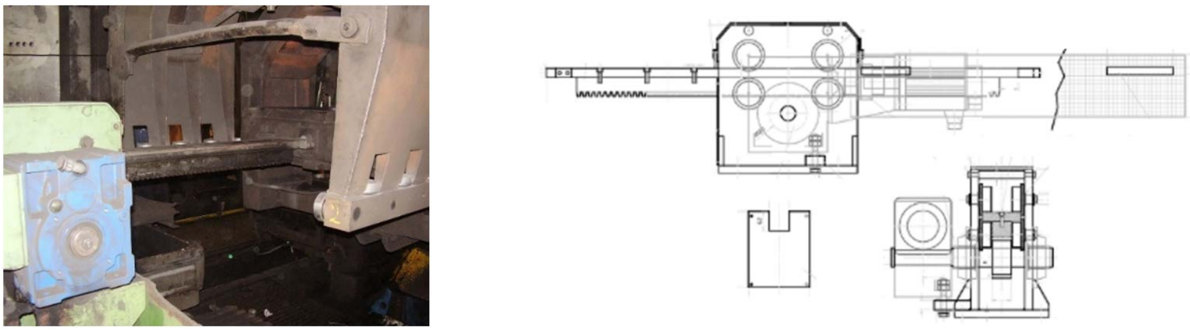
2.6 Servo-Actuated Bracket Pusher Unit (Functional Sub-Unit)

The servo-actuated bracket pusher unit cell is a key subsystem within a pneumatic molding designed to precisely move the brackets (the frames that define the sand mold) along the production cycle. The movement is driven by a brushless motor, coupled with a gearbox and a rack-and-pinion system, which converts rotary motion into linear translation. The assembly is integrated into a structure equipped with limit switches, roller guides, and fastening elements, ensuring accuracy, reliability, and safety during operation. It can be highlighted:

- Pestle head, with critical issues found in the seals and roughness of the seats.

- Translation linkage, with potential criticalities especially in the connecting rod-pin connections and in protecting the bearings from dust.

- Brushless motor pusher acts moving the bracket inside the pneumatic forming cell, paying particular attention to ensuring precise and controlled positioning of the bracket inside the system, thus contributing to a more efficient and repeatable forming process. The specific solution with a brushless motor (Figure 6) offers several advantages such as high precision and movement control, reducing positioning errors to a minimum; low maintenance compared to brushed motors, thanks to the absence of electrical contacts subject to wear; greater energy efficiency, optimizing consumption during the forming cycle; improved dynamics, with rapid response to commands and the possibility of fine adjustment of the thrust.



(a) (b)

Figure 6. Servo-actuated bracket pusher unit cell: (a) real-life view; (b) technical drawing

3 Results and Discussion

3.1 Functional Analysis

The pusher is functionally integrated with several other components that regulate its stroke and movement. Its operation is made possible by the interaction between motion transmission systems, position control devices, and support structures that ensure its alignment and stability (Figure 7).

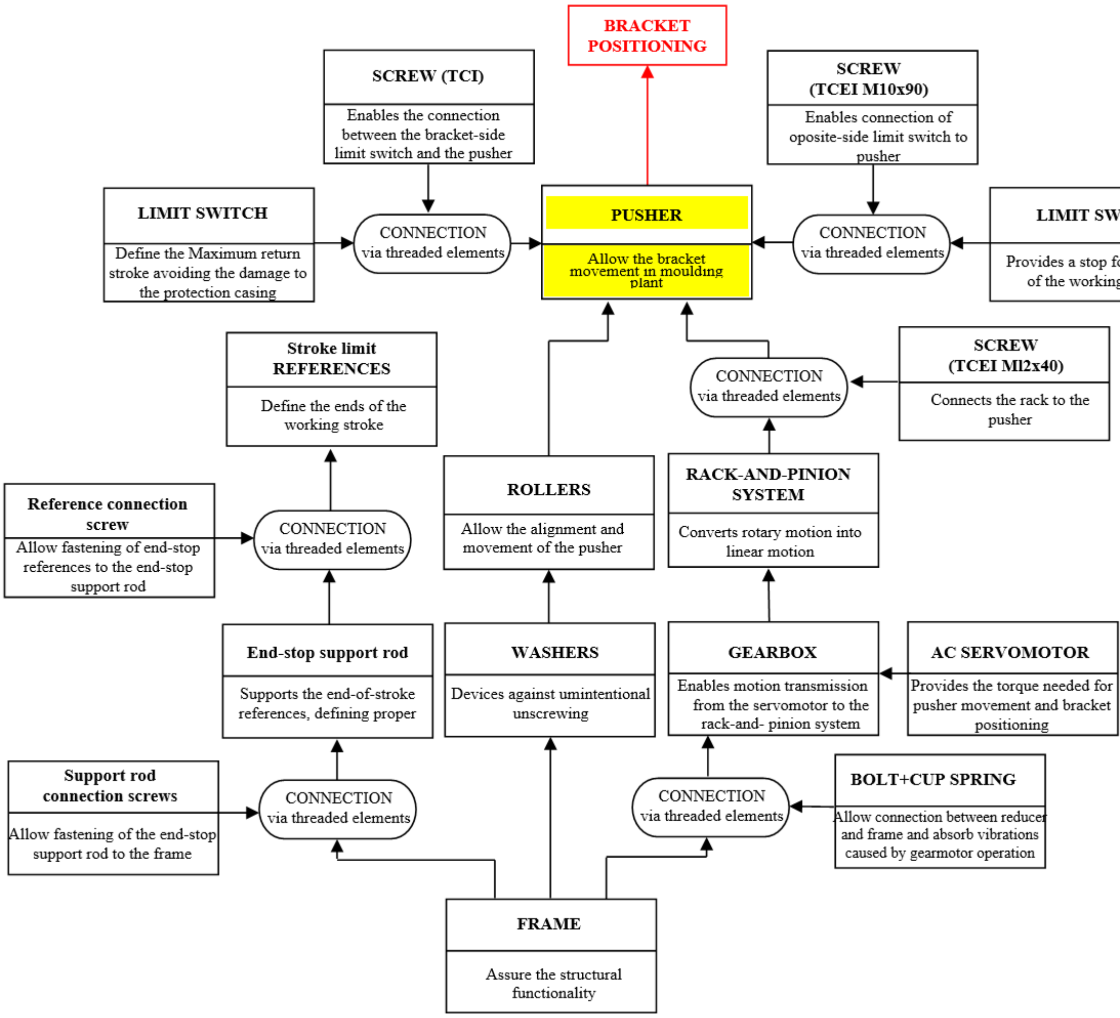


Figure 7. Functional diagram of the pusher inside the forming system

Specifically, the movement of the pusher is generated by the brushless servomotor, which provides the torque necessary for translation. The mechanical energy produced by the motor is transferred through a gearbox, which adapts its characteristics in terms of speed and torque and then transmits it to the rack and pinion system. The latter has the task of converting the rotary motion into a linear motion, thus allowing the controlled sliding of the pusher along its operating stroke. To ensure that the movement of the pusher occurs within defined limits, various limit switch references are provided. These elements delimit the ends of the working stroke, preventing unwanted movements and protecting the components from possible impacts or overloads. The references are fixed to a support structure, which not only guarantees their stability but also allows their position to be adjusted according to operational needs. These devices prevent the stroke from exceeding the maximum permitted value, thus avoiding the risk of damage to the mechanical protections and ensuring safe operation. The limit switches are connected to both the support structure and the pusher itself, creating a direct interaction that allows you to monitor and adjust the movement in real time. In addition to the stroke-limiting function, the system also includes a connection between the pusher and the motion transmission mechanism, which occurs via threaded organs. This connection allows the motion of the servomotor to be transferred directly to the pusher, ensuring an immediate and precise response to the commands given by the control system. The presence of elastic elements, such as compensation springs, helps absorb any vibrations resulting from the operation of the gearmotor, keeping the movement stable. The support structure of the pusher is then connected to a series of rollers, whose task is to ensure correct alignment during movement. The rollers reduce friction and guide the movement along the established path, avoiding deviations that could compromise the precision of the positioning. The fixing elements, such as the connecting screws, also play an important role in maintaining a firm connection between the pusher and the other components of the system, ensuring effective transmission of the force exerted by the motor.

Overall, the pusher is part of a system in which each component plays an essential role in the correct execution of the forming process. The integration between the motor, the gearbox, and the rack-and-pinion system allows the translation of the pusher, while the limit switches, the references, and the rollers ensure that the movement occurs in a controlled and precise manner. Finally, the support structure provides the necessary mechanical support and allows the system configuration to be adjusted according to production needs.

3.2 Criticality Analysis

The FMECA outputs are reported in Table A1 and Table A2, proposed according to a conventional formulation, providing a structured examination of the critical components, highlighting N. 5 on 16 key components, and specifying for each one the function, failure modes, causes, effects, detection methods, as well as the numerical evaluations of severity, probability, and detectability:

- Servomotor, the central element for the movement of the brackets. Its main failure mode is failure to operate or stop during operation, a condition that can result from breakage due to wear, a defective component or electrical problems. This type of failure would result in a loss of torque, compromising the entire movement process. The assigned severity is 6, with a moderate probability (3) and a low detectability (10), which leads to an RPN of 180, signaling a critical area to monitor.

- Gearbox, which allows the transmission of motion from the servomotor to the system, is subject to a similar problem: failure of motion transmission due to breakage due to wear, incorrect assembly or manufacturing defects. Again, the consequence is failure of the pusher to move, with an estimated severity of 6, a lower probability (2), and an equally low detectability (10), leading to an RPN of 120.

- Cup spring connection, responsible for the connection between the gearbox and the frame. Its criticality is related to a potential connection failure, which could generate vibrations and damage to the entire system. This failure is less likely (1), but with a higher severity (7), a slightly better detectability (9), and a lower RPN than the previous components (63).

- Rack and pinion system: its task of transforming rotary motion into rectilinear motion implies that a failure to transmit motion is a critical problem, with direct effects on the movement of the pusher. Again, the severity is 7, the probability of occurrence is low (1), and the detectability is 9, with an RPN of 63, a value similar to that of the bolt.

- Pusher, responsible for moving the brackets, may be misaligned from its established position, which may compromise the correct operation of the system. The risk is significant (severity 7), although the probability is low (1), and the detectability is very poor (10). The RPN is 70, indicating a need for intervention that is less of a priority than the servomotor.

Figure 8 provides a visual identification of critical components within the servo-actuated bracket pusher unit, based on FMECA results. It highlights high-risk elements such as the servomotor and the gearbox, whose RPN values exceed the defined threshold.

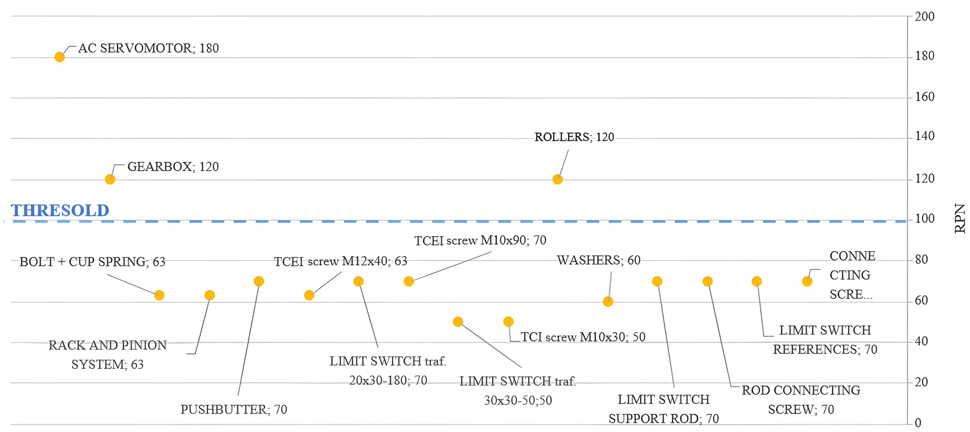


Figure 8. Identification of critical components within the servo-actuated bracket pusher unit based on FMECA results, highlighting high-risk elements such as the servomotor and gearbox

The analysis shows that the most critical components in terms of risk are the servomotor (RPN 180), followed by the gearbox and the rollers, both with RPNs of 120. These values exceed the defined criticality threshold of 100, making them the main areas of intervention. This is consistent with their key roles in the transmission and guidance of motion within the handling system. The low detectability (score 10) associated with these components highlights a weakness in the current control methods, suggesting that improvement actions should focus on the introduction of more effective monitoring systems, such as advanced diagnostic sensors or automated feedback controls. For other components, such as the rack and pinion system and the cup spring bolt, the RPN values remain below the criticality threshold, indicating a lower priority for intervention, even though their failure could still generate harmful effects if not properly controlled.

3.3 Improvement Analysis

The FMECA analysis highlighted a very small number of critical issues, specific to the stirrup handling system, identifying the servomotor, the gearbox and the rollers as the elements worthy of greater attention. For each of these components, targeted actions were proposed to reduce the probability of failure and improve the overall reliability of the system.

A fundamental corrective action involves monitoring the health status of the servomotor and the gearbox. The installation of temperature and vibration sensors would allow us to detect any anomalies before the failure occurs, allowing preventive interventions and improving the operational continuity of the system. Similarly, for mechanical components subject to prolonged stress, such as the cup spring bolt, a periodic check of the tightening and the use of materials with greater resistance to fatigue are recommended. This would reduce the risk of structural failures and possible damage to the system.

For the rack and pinion system, the risk of motion transmission failure can be mitigated by improving the lubrication system and increasing visual inspections. Finally, for the pusher, an automatic alignment check using laser or optical sensors could increase the detectability of any misalignments before they become critical failures. Specifically, the three suggested interventions are:

1. Servomotor for the risk of failure to operate or stopping during operation. The initial analysis identified the servomotor as the component with the highest risk index (RPN 180) due to possible breakages due to wear, manufacturing defects or electrical problems. To reduce this risk, a check of the sizing of the gearmotor is recommended. The effort required for this action is low, but it results in a significant reduction in the probability of failure, going from 3 to 1, with a reduction of the RPN to 60.

2. Gearbox for the risk of failure of motion transmission. Similarly, the gearbox has an initial RPN of 120, with similar causes related to failure due to wear or assembly defects. The suggested corrective action consists of checking the sizing of the gearbox and the belt, with an immediate impact on reducing the probability of failure from 2 to 1, keeping the severity unchanged (6). The final RPN is thus lowered to 60, ensuring greater reliability of the entire system.

3. Rollers for the risk of failure to move. The analysis highlighted the importance of rollers in the alignment and movement of the brackets. A possible failure, related to manufacturing defects or wear, had an initial RPN of 120. To mitigate this risk, a verification of the rollers' sizing is proposed, with a medium commitment and the advantage of avoiding degraded operation. Also in this case, the probability of failure is reduced from 2 to 1, bringing the RPN to 60.

3.4 Further Considerations

The improvement analysis shows that the revision of the sizing of critical components is an effective strategy to lower the risk of failure, significantly reducing the RPN. In all the cases analyzed, the risk index, already quite low, was further halved, going from values between 120 and 180 to ≤ 60 (out of 1,000), with, therefore, a further drastic decrease in the probability of malfunction.

A key aspect that emerges is that the criticalities found do not necessarily derive from design flaws, but rather from suboptimal component choices. This underlines the importance of a rigorous verification not only of the engineering calculations and operating conditions during the design and maintenance phase, but also in the choice of systems necessary for the assemblies.

From an operational point of view, the suggested corrective actions require low effort, being easily implementable without significant impacts on production or operating costs. This is a crucial element for the casting industry, where FMECA adoption is still not widespread and requires practical demonstrations of effectiveness to be adopted on a larger scale.

4 Conclusions

The integration of improvement actions into the FMECA process has demonstrated how the main critical issues of stirrup handling can be effectively mitigated with targeted and easy-to-implement interventions. The approach adopted not only identifies problems, but also offers concrete and practicable solutions, contributing to improving the overall reliability of the system.

This analysis confirms the value of FMECA in the smelting context and reinforces the importance of a structured approach to risk management. The suggested improvements demonstrate that significant operational benefits can be achieved without the need for costly investments or radical changes to production processes, making the adoption of this methodology a strategic choice for the optimization of industrial production.

Author Contributions

Authors contributed equally to all stages of the research and manuscript preparation, including conceptualization, methodology, software development, validation, formal analysis, investigation, data curation, writing (both original draft and review), visualization, supervision, project administration, and funding acquisition. All authors have read and approved the final version of the manuscript.

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Data Availability

The data that support the findings are available from the corresponding author, upon reasonable request. This data includes detailed FMECA reports, operational logs from the foundry, and outcomes of the implemented improvements, which are essential for replicating the study or conducting further research in this area.

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Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Table A1. FMECA table

	Component	Function	Failure Mode	Failure Cause	Failure Effect	Detection Mode	Severity	Probability	Detectability	RPN	Critical RPN
1	AC servo-motor	Provides the torque needed to move the bracket positioning pusher	Failure to operate/stop during operation	Breakdown: 1) defective component 2) wear 3) fatigue 4) seizure 5) undersizing 6) winding breakage due to overvoltage or mechanical stress 7) oxidation Absence of signal from PLC	Loss of torque required to move the parts	Visual control Signaling on PLC	6	3	10	180	100
2	Gearbox	Allows the transmission of motion from the servomotor to the rack and pinion system	Failure to transmit motion	Breakage: 1) defective component 2) wear 3) fatigue 4) seizure Breakage of the toothed belt for transmission of motion from the servomotor to the Gearbox	Pusher movement failure	Visual check Signalling on PLC (system block due to impossibility of pushing device movement)	6	2	10	120	100
3	Bolt + cup spring	They allow the connection between the Gearbox and the frame and the absorption of vibrations due to the operation of the gearmotor	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations 3) inadequate cup springs	Excessive vibrations Damage to rack and pinion system	Visual check Signalling on PLC (system block due to impossibility of pushing device movement)	7	1	9	63	100

Continued

	Component	Function	Failure Mode	Failure Cause	Failure Effect	Detection Mode	Severity	Probability	Detectability	RPN	Critical RPN
4	Rack and pinion system	Transform circular motion into rectilinear motion	Failure to transmit motion	Breakdown: 1) defective component 2) wear 3) fatigue 4) seizure	Pusher movement failure	Visual check Signalling on PLC (system block due to impossibility of pushing device movement)	7	1	9	63	100
5	Pushbutter	Allows the movement of the brackets in the forming plant	Failure to move	Localized failure of contact surface with sliding rollers	Pusher misalignment with bracket position	Visual inspection	7	1	10	70	100
6	TCEI screw M12x40	Allows connection between rack and pusher	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations	Excessive vibration Excessive pusher deflection	Visual inspection	7	1	9	63	100
7	Limit switch traf. $20 \times 30 - 180$	Make a joke for the extremes of the working stroke	Missed/incorrect end of stroke	Breakage: 1) defective component 2) wear 3) fatigue 4) undersizing	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100
8	TCEI screw M10x90	Allows connection between the limit switch on the opposite side of the bracket and the pusher	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100

Continued

Component		Function	Failure Mode	Failure Cause	Failure Effect	Detection Mode	Severity	Probability	Detectability	RPN	Critical RPN
9	Limit switch traf. $30 \times 30 - 50$	Defines the maximum return stroke avoiding damage to the protective casing	Missed/incorrect end of stroke	Breakage: 1) defective component 2) wear 3) fatigue 4) undersizing	Damage to the pusher protection casing	Visual inspection	5	1	10	50	100
10	TCI screw M10x30	Allows connection between bracket side limit switch and pusher	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations	Damage to the pusher protection casing	Visual inspection	5	1	10	50	100
11	Rollers	They allow the alignment and movement of the pusher	Failure to move	Breakage: 1) defective component 2) wear 3) undersizing	Failure to move bracket in forming plant	Visual inspection	6	2	10	120	100
12	Washers	Devices against spontaneous unscrewing	Insufficient pressure	1) Insufficient clamping preload 2) Vibrations	Failure to move bracket in forming plant	Visual inspection	6	1	10	60	100
13	Limit switch support rod	It supports the extreme references of the working stroke by defining the appropriate working positions through slots	Lack of support	1) defective component 2) fatigue 3) undersizing	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100

Continued

Component		Function	Failure Mode	Failure Cause	Failure Effect	Detection Mode	Severity	Probability	Detectability	RPN	Critical RPN
14	Rod connecting screw	They allow the limit switch support rod to be fixed to the frame	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100
15	Limit switch references	They allow you to define the extremes of the working stroke	Missed/incorrect end of stroke	Breakage: 1) defective component 2) wear 3) fatigue 4) undersizing	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100
16	Connecting screw limit switch references	They allow you to fix the limit switch references to the limit switch support rod	Connection failed	Breakage: 1) defective component 2) fatigue Spontaneous unscrewing: 1) insufficient tightening preload 2) vibrations	Excessive push on the bracket train resulting in misalignment between the bracket and the pusher head, damaging the pusher protection casing	Visual control Signaling on PLC (system block due to impossibility of forming brackets)	7	1	10	70	100

Note: S – Severity; P – Probability; D – Detectability; RPN – Risk Priority Number; TH - Threshold

Table A2. FMECA table limited to critical issues (i.e. RPN > 100) and reccomended actions

Component		Function	Failure Modes	Failure Causes	Recommended Actions	Effort Required	Awaited Benefits	Severity	Probability	Detectability	RPN	Threshold
1	AC servomotor	Provides the necessary torque for the positioning and movement of the pusher brackets	Failure to operate/stop during operation	Breakage: 1) defective component 2) wear 3) fatigue 4) seizure 5) undersizing 6) winding break due to overvoltage or mechanical stress 7) oxidation Absence of signal from PLC	Check motor-drive sizing; Plan wiring check during maintenance	Low	Reduction of failure probability	6	1	10	60	100
2	Gearbox	Allows the transmission of motion from the servomotor to the pinion-rack system	Failure to transmit motion	Breakage: 1) defective component 2) wear 3) fatigue 4) seizure; Breakage of the timing belt for motor transmission from the servomotor to the gearbox	Check sizing of Gearbox and timing belt for motor transmission	Low	Reduction of breakdowns leading to machine stops	6	1	10	60	100
11	Rollers	Allow the alignment and movement of the pusher	Failure to move	Breakage: 1) defective component 2) wear 3) undersizing	Check sizing of rollers	Medium	Prevents degraded operation	6	1	10	60	100

Note: S – Severity; P – Probability; D – Detectability; RPN – Risk Priority Number; TH - Threshold