
Optimizing cement kiln operation with expert systems

R. Fernández¹, L. Sevilla¹, Juan M. Cañero-Nieto¹

¹ Civil, Materials and Manufacturing Engineering Department, Universidad de Málaga, Spain.

r.fernandez@uma.es

Keywords: Expert systems, advanced process control (APC), process optimization, cement industry

Abstract

The optimization of cement kilns presents a significant challenge for the industry, where achieving operational efficiency and sustainability is paramount. This study introduces a Kiln Expert System (KES) that leverages symbolic artificial intelligence, real-time data analysis, and adaptive algorithms to dynamically stabilize key variables such as calciner temperature and oxygen levels. By incorporating a higher proportion of alternative fuels (ATFs), KES not only reduces variable costs but also minimizes the carbon footprint and strengthens the competitive positioning of operations.

Deployed in a facility with a five-stage preheater and a multistage calciner, the KES fine-tunes the combustion parameters in real time to maintain high production standards, improve performance, and adapt to changing operational conditions. This innovative approach demonstrates how AI-driven systems can transform process management by enabling precise control, optimizing resource use, and aligning industrial practices with environmental goals.

Introduction

The cement sector is one of the main emitters of CO₂ and is responsible for approximately 26% of industrial emissions and 8% of global emissions. This significant environmental impact highlights its crucial role, along with other large industries, in the sustainability of natural resources and the mitigation of global warming. However, this sector is facing a dynamic and highly competitive environment that demands innovative and sustainable solutions [1].

A considerable portion of the emissions and energy consumption associated with the manufacture of cement are unavoidable because of inherent chemical reactions, such as decarbonation, and the intensive nature of the processes involved. This significantly contributes to the carbon footprint of the final product [2].

Tightening environmental regulations and increasing pressure to reduce carbon footprints are forcing companies to implement strategies that optimize their processes and bolster their competitiveness. Energy efficiency and sustainability are essential for ensuring long-term business success [3].

The adoption of advanced technologies such as carbon capture and storage (CCS) and the use of alternative fuels (ATFs) have become effective tools for mitigating greenhouse gas emissions. Similarly, digitalization and artificial intelligence are transforming the management of production processes, allowing more accurate and efficient monitoring, improving productivity, and ensuring compliance with regulations. These technological innovations demonstrate the feasibility of transforming industrial processes to balance economic growth and environmental preservation, thereby laying the foundation for a sustainable and responsible future [4 - 5].

Clinker manufacturing, a fundamental and energy-intensive stage in the cement production process, is responsible for most emissions associated with the cement manufacturing process. This intermediate material is produced by calcining a mixture of limestone, clay, and other components in rotary kilns that reach temperatures of up to 1,450 °C. During this process, essential chemical reactions occur, such as the decomposition of limestone into calcium oxide

and carbon dioxide as well as the formation of calcium silicates and aluminates, which are key compounds for cement quality [2, 6-7].

In addition, as energy accounts for up to 70% of the variable costs in a cement factory, 33% is linked to the thermal energy used in the kiln, and 37% to electrical energy, enhancing energy efficiency and substituting fossil fuels with alternative options are critical challenges. These efforts not only reduce operating costs and greenhouse gas emissions but also align with corporate social responsibility objectives [8 - 9].

In the past, the optimization of industrial processes was supported by traditional control systems such as Proportional, Integral, and Derivative (PID) controllers, which were designed to reactively adjust independent variables. These tools improved operational stability and made significant gains in efficiency but relied heavily on constant operator supervision. In addition, they face significant limitations in managing the complexity and interdependence of multiple critical variables, such as calciner temperature or oxygen levels in the kiln [10].

Over time, Model-Based Predictive Control (MPC) has undergone a significant shift, owing to the introduction of initiative-taking approaches. This system uses mathematical models to anticipate the behavior of the process and makes dynamic adjustments, allowing more precise control to adapt to the operating conditions. The adoption of MPC laid the foundation for the development of more advanced technologies aimed at addressing the increasing complexity of the processes and challenges in the sector [11-12].

The advent of expert systems based on symbolic artificial intelligence represents a milestone in the field of advanced automation [13]. These tools integrate the specialized knowledge of production engineers into explicit rule logical structures, facilitating the management of multiple interdependent variables. Expert systems have established themselves as precise, stable, and efficient process-control technologies, making them essential in the cement industry. However, their implementation in real-world plants remains limited, highlighting the need for more comprehensive models and validations in industrial environments [14-16].

In contrast, sub-symbolic artificial intelligence offers optimization capabilities through technologies, such as neural networks and machine learning algorithms. These tools analyze large volumes of data in real time, identify complex patterns, and dynamically adjust the operational targets. This approach is particularly useful for managing the variability inherent in cement processes and increasing responsiveness to fluctuations in operating conditions [17-19].

The future of the industry lies in neurosymbolic computing, which fuses the structured precision of symbolic artificial intelligence with the adaptability and continuous learning capabilities of sub-symbolic AI. This technological integration allows for the development of more resilient and flexible operating models capable of addressing challenges from complementary perspectives [20-21].

The proposed Kiln Expert System (KES) represents a natural evolution in process automation, marking its first validation within a real production environment. Its integrated maintenance strategies are designed to set a benchmark for kiln optimization. The primary objective of implementing this system is to achieve significant improvements in energy efficiency, maximize the utilization of alternative fuels (ATFs), minimize human intervention, and enhance operational stability. Moreover, the system is inherently designed to accommodate future advancements in subsymbolic artificial intelligence, enabling the seamless integration of emerging technologies to ensure continuous process optimization.

Methods

The implementation of an expert system involves analyzing and modeling process variables to develop a comprehensive management strategy, ensuring operational efficiency and minimal error margins. The benefits include consistent product quality, reduced energy consumption, and optimized use of ATFs. Enhanced temperature control minimizes errors, while indirect advantages, such as extended equipment life, intuitive interfaces, and advanced system modeling, improving decision-making and process efficiency. Expert systems also enable remote operation, decrease on-site dependency, and boost operational efficiency. By automating complex tasks and responding in real time, systems such as the KES align cement production with sustainability goals and global market demands, fostering long-term competitiveness and environmental responsibility.

Description of the installation. The KES was successfully implemented in a modern cement plant with a nominal production capacity of 3300 tons of clinker per day. This system was integrated into an installation equipped with a five-stage preheater, as illustrated in Figure 1.

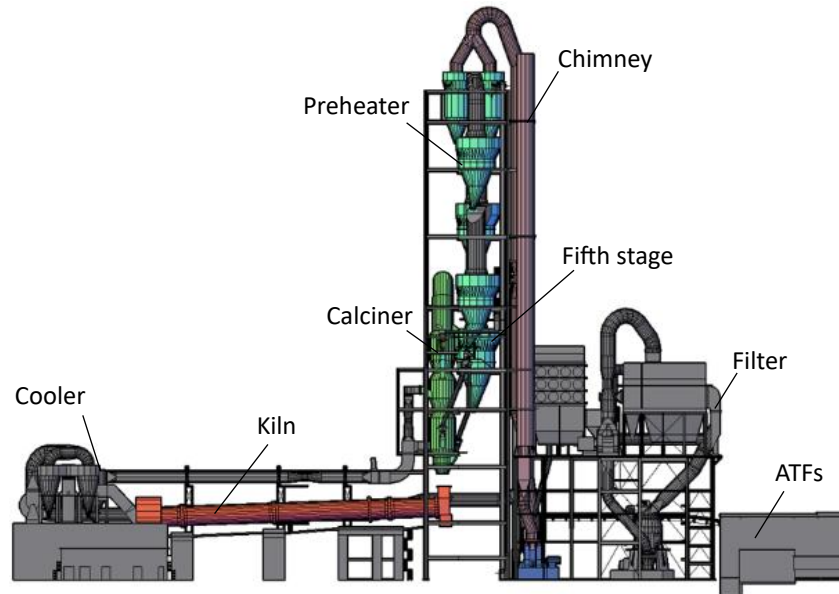


Figure 1. A typical preheater installation with five stages.

The facility features a five-stage preheater and a multistage calciner designed to reduce emissions and enhance the thermal efficiency. A grate cooler maximizes clinker cooling and recovers heat for reuse, supported by ATFs dosing systems for the calciner and the main burner. Strategically placed gas analyzers monitor the critical parameters at the kiln inlet, preheater outlet, and chimney. The combustion system includes a main burner, calciner secondary burner, and low-NO_x tertiary burner.

The Siemens PCS7 platform integrates advanced digital control and automation with programmable controllers that are housed in a central technical room. Decentralized electrical rooms connected via a high-speed fiber-optic network ensure efficient subsystem management and robust communication, thereby creating an ideal environment for KES implementation.

Process description. The clinker manufacturing process begins with the extraction, crushing, and mixing of limestone, clay, and corrective materials in controlled proportions to achieve the required particle sizes and chemical compositions. The mixture was homogenized to ensure uniformity and chemical consistency, thus meeting laboratory specifications.

The raw material is fed into the preheater, where the material reaches temperatures close to 900 °C, as it descends through a fluidized bed countercurrent to the combustion gases. This process dries the material, removes volatile components, and decomposes calcium carbonate into calcium oxide and carbon dioxide. The partially decarbonized material then enters the rotary kiln, where it is progressively heated to approximately 1,450 °C, triggering key chemical reactions. Liquid phases form, allowing silica, alumina, and iron oxides to interact and produce primary clinker compounds, alite, and belite. The hot clinker is rapidly cooled to stabilize its crystalline structure, yielding a high-quality product suitable for cement production.

Contextualization and objective definition. As the first phase of implementation, with the aim of minimizing operational risks, it was agreed, in collaboration with the plant personnel, to limit the initial scope to the effective control of combustion in the calciner. This decision was based on the critical influence of the calciner on the thermal stability of the kiln and the variable operating costs.

Efficient calciner combustion is crucial for proper raw meal decarbonation, optimizing the use of ATFs, and reducing emissions. However, the heterogeneity of ATFs, such as tires and pellets, causes instability, increased CO emissions, and dosing facility blockage. To overcome these challenges, precise control of oxygen and CO concentrations was prioritized, ensuring stable and efficient combustion under varying conditions. The maximum temperature thresholds were set to protect the refractory and maintain the integrity of the calciner. This collaborative strategy identifies and mitigates operational issues, laying a solid foundation for future KES expansion while enhancing operator acceptance and confidence in the system.

Control strategy and modeling. Control strategies and system modeling are vital in developing expert systems using symbolic AI to replicate and optimize human decision-making in complex operations. This process requires a thorough understanding of the structural and functional dynamics of the facility, and the specific chemical processes involved. Identifying the interdependencies between the key variables ensures operational stability and robust control. Building this strategy requires interdisciplinary collaboration and integrating best practices from engineers, operators, and AI specialists. Mathematical models, such as energy and mass balances, combined with heuristic rules from operators, create a control scheme that merges expert knowledge, modeling, and AI tools. This ensures adaptive decisions are based on a comprehensive understanding of the process. Unlike traditional PID controllers, KES incorporates advanced process control techniques, focusing on calciner temperature and combustion. It effectively manages the fuel-oxygen relationship to prevent incomplete combustion and maintain process balance.

Figure 2 shows a block diagram representing the temperature control implemented in the calciner, highlighting its ability to integrate the operation of various fuels and ensure optimal combustion conditions.

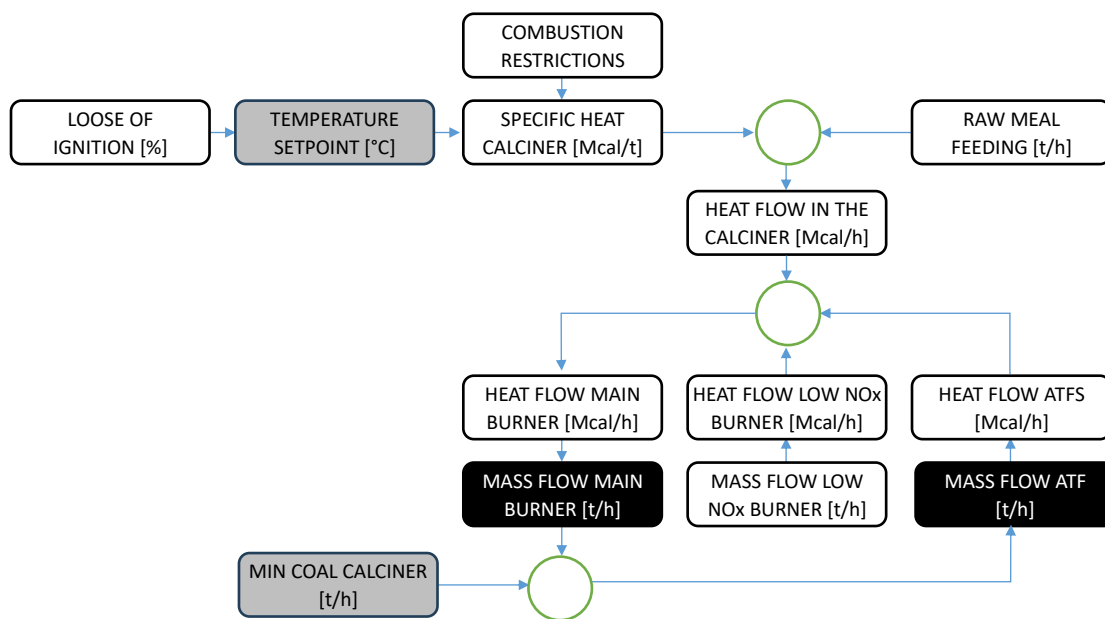


Figure 2. Modeling of the calciner control operation.

The temperature regulator (Fig. 2) operates independently of fuel type, adjusting thermal flow based on production fluctuations for stability and efficiency. It enables real-time fuel substitution, optimizing flexibility and energy use. Analyzing fuel transport times improves energy variation predictions, mitigates disturbances, and enhances system responsiveness. This integration improves combustion control, reduces energy waste, and ensures adaptive kiln operation. Expert actions protect the calciner by monitoring temperature variations, while automated fuel reduction prevents overheating. A module maximizes ATF use, reducing fossil fuel reliance through predictive algorithms. A second regulator controls the kiln's intermediate fan, maintaining optimal oxygen levels for efficient combustion. It

dynamically adjusts fan speed to stabilize processes, minimize pressure drops, and optimize energy consumption. These innovations solidify KES as a transformative kiln solution.

Application development. The KES was designed as a modular and scalable solution for long-term sustainability and improvement. Developed collaboratively with plant technicians, its open-source inference engine integrates seamlessly into the DCS using Siemens PCS7 and Simatic Manager. Advanced Process Libraries (APL) ensure compatibility, efficient parameterization, and direct PLC implementation, enhancing execution speed and performance while reducing reliance on external communications. This approach addresses traditional symbolic AI limitations and optimizes system functionality within the infrastructure of a plant.

To enhance the robustness against instrumentation failures, status signals were configured to continuously monitor critical process variables. Redundancies in key sensors, including temperature, O₂, and CO, ensure operational continuity by automatically switching to alternative data sources during anomalies. Dynamic regulator limits, adjusted in real time, maintain optimal control under variable conditions. Graphical interfaces developed with Siemens WinCC emphasized simplicity and adaptability, enabling intuitive operator interaction. These interfaces display real-time operating variables, alarms, and notifications using clear visuals and color-coded alerts. Operators could directly adjust parameters, while advanced alarm management prioritized critical issues, ensuring efficient process control and responsiveness to operational needs.

To minimize implementation risks, exhaustive virtual validation was conducted using Siemens PLCSIM, emulating input and output signals and testing algorithm responses under various conditions. Simulations ensured error-free integration, identified inconsistencies, optimized logic, and enhanced stability, thus ensuring system readiness before deployment in the production environment.

Industrial implementation. To overcome barriers in implementing expert systems, such as operator acceptance and iterative development, a detailed plan involving process engineers and kiln operators ensures a smooth transition and KES adaptation to plant conditions. Customized training sessions familiarize the staff with KES interfaces, alarm management, and manual settings through simulations of operational scenarios. This validated the compatibility and facilitated necessary adjustments.

In collaboration with maintenance and automation teams, a thorough assessment of the kiln control system identified suitable PLCs by analyzing memory, capacity, and cycle time. The validated application was installed with the output variables disconnected during the initial tests to ensure safe integration. Open-loop validation confirmed the stability of the application before the actuators were connected for closed-loop operation. Gradual activation enables active monitoring, precise adjustments, and optimization of control loops, including gains and response times. The final acceptance tests simulated failures and maximum load scenarios to evaluate KES performance. The system proved effective in responding to critical events, maintaining stability, and delivering accurate real-time data for decision making. These efforts confirmed that KES is a key tool for stabilizing kiln operations, ensuring continuity, and supporting continuous improvement, reinforcing its role in achieving operational efficiency and reliability across the plant.

Result and discussion.

The KES was developed and implemented in collaboration with process engineers at a modern cement plant, equipped with advanced technologies such as a five-stage preheater and a multistage calciner. After analyzing the operational needs, the initial implementation focused on calciner control, leveraging expertise in process control. The KES distinguishes itself from an innovative strategy for managing process disturbances, such as ATF variability, and addresses nonlinear interdependencies and dynamic complexities in cement production. This advanced solution enhances operational stability, efficiency, and adaptability to variable conditions, offering significant improvements over traditional systems.

Challenges encountered. The implementation of KES faced challenges, including initial operator resistance owing to skepticism about advanced automation and its impact on daily tasks [22]. Concerns about managing complex real-world scenarios highlight the need to build trust and engage work teams. Sensor calibration and inadequate instrumentation for determining ATF calorific values in real time pose additional difficulties because fuel variability impacts system stability. Integrating KES with existing PLCs and servers requires multidisciplinary collaboration to

ensure technical and operational safety. Intuitive human-machine interfaces (HMIs) with clear displays and real-time alarms facilitated the transition, while active staff involved in system design and customization ensured technological acceptance and laid the groundwork for long-term success.

Operational performance. To evaluate the impact of KES on clinker production efficiency, sustainability, and stability, key performance indicators (KPIs) were analyzed, including ATFs substitution, calciner temperature deviation, and error percentage relative to setpoints. These metrics assessed the thermal regulation accuracy and the ability of the system to manage variable fuel properties.

Owing to the complexity of clinker production and variable operating conditions, a twenty-five-month comparative study was conducted, including a reference phase and the period after KES implementation. This analysis provided reliable insights into performance improvements, with Table 1 highlighting the enhancements in thermal stability and key process parameters achieved through KES integration.

Table 1. Comparison of calciner temperature before and after the implementation of KES.

<i>Period [months]</i>	<i>STD Deviation [°C]</i>	<i>Max Deviation [°C]</i>	<i>Relative Error [%]</i>	<i>Type of Control</i>
8	15.00	19	0.76	<i>Traditional</i>
17	8.31	13	0.21	<i>KES</i>

Before the implementation of the KES, the traditional control system recorded calciner temperature deviations of up to 19 °C with an average deviation of 15 °C and an error of 0.76% relative to the setpoint. These fluctuations limit the use of ATFs and pose operational challenges. After the KES installation, real-time fuel adjustments and advanced control algorithms significantly improved stability. The standard deviation dropped to 8.31 °C, and the error decreased to 0.21%, reflecting a 44.6% improvement in thermal stability and over 70% error reduction. These enhancements increased the utilization of ATFs, as shown in Table 2, which compares the fuel usage before, during, and after the system implementation.

Table 2. Comparison of the use of ATFs before and after KES.

<i>Years</i>	<i>ATFs Calciner [%]</i>	<i>ATFs Kiln [%]</i>	<i>ATFs Total [%]</i>	<i>Type of Control</i>
1	31.85	6.75	38.6	Traditional
2	37.86	8.74	46.6	Transition
3	39.26	5.54	44.8	KES
4	46.53	4.57	51.1	KES
5	49.1	0.4	49.5	KES

During the reference period, the traditional control system limited ATFs use in the calciner to 31.85%, owing to temperature instability. A risk-mitigation strategy in year two ensured a smooth transition to the KES. After its implementation in year three, ATF usage increased to 39.26%, reaching 46.53% in year four and 49.1% in year five.

The system’s implementation enhanced temperature stability, ensuring consistent fuel combustion and reducing energy consumption. Optimized ATF management decreased fossil fuel dependence and minimized unburned carbon residues, lowering the carbon footprint. These efficiency gains also protected the refractory calciner, lowering maintenance costs and reinforcing kiln sustainability. Additionally, intuitive interfaces and advanced modeling improved decision-making, enabling real-time optimization and ensuring long-term efficiency. These advancements align with studies demonstrating how expert systems stabilize complex industrial processes, highlighting the crucial role of advanced technologies in driving sustainability and cost-effectiveness in the cement industry [9, 22 - 23].

Conclusion.

The implementation of the Kiln Expert System (KES) has represented a significant step towards operational excellence and sustainability in cement manufacturing. This system is crucial for increasing the thermal stability of calciners and promoting the use of Alternative Fuels (ATFs). Owing to its application, the average standard deviation of the temperature in the calciner was reduced from 15 °C to 8.31 °C, achieving remarkable stabilization of the process. This made it possible to increase the proportion of ATFs used in the calciner from 31.85% to 49.1% over a five-year period, optimizing the fuel mix, reducing operating costs, and reducing CO₂ emissions. These advances have generated a positive environmental impact by promoting a more efficient and environmentally friendly operation in line with the industry's sustainability objectives.

Despite these advantages, expert systems face challenges in terms of scalability, adaptability, and maintenance, and require specialized skills that may be difficult for resource-limited plants. Sensor calibration and inadequate instrumentation complicate process modeling, whereas operator skepticism hinders its adoption. Successful implementation requires robust algorithm design, seamless human integration, and interdisciplinary collaboration among engineers, AI specialists, and maintenance teams. Engaging operators in system design and calibration improves acceptance, ensuring a smoother transition to automation and enhancing system performance, stability, and long-term operational success. Addressing these challenges is essential for fully realizing the benefits of expert systems in industrial environments.

The next steps involve integrating advanced artificial intelligence techniques, such as neural networks and genetic algorithms, with traditional expert systems to optimize manufacturing costs and reduce emissions. These improvements can leverage factors such as sales forecasts and electricity prices. In addition, expanding the application of expert systems to other energy-intensive industries, such as lime and steel production, would enhance their impact. The development of scalable methodologies is also essential to ensure that small- and medium-sized plants can adopt these technologies effectively.

In conclusion, expert systems have demonstrated their ability to optimize cement kiln operations by balancing energy efficiency, operational stability, and environmental sustainability. Although technical and operational challenges persist, their transformative potential is undeniable. Continued investment in R&D will drive innovation, enabling expert systems based on neurosymbolic computing to shape the future of industrial processes.

Acknowledgments.

We are deeply grateful to Heidelberg Materials for their significant contributions and for providing the industrial resources essential for validating the proposed system. We also extend our heartfelt gratitude to Universidad de Málaga-Campus de Excelencia Internacional Andalucía Tech for their invaluable support and collaboration.

References

- [1] Guo, Y.; Luo, L.; Liu, T.; Hao, L.; Li, Y.; Liu, P.; Zhu, T. (2024). A review of low-carbon technologies and projects for the global cement industry. *J. Environ. Sci.*, 136, pp. 682–697. <https://doi.org/10.1016/j.jes.2023.01.021>
- [2] Alsop, P. A.; Chen, H.; Chin-Fatt, A. L.; Jackura, A. J.; McCabe, M. I.; Tseng, H. H. (2001). *The Cement Plant Operations Handbook*, 7th ed. Tradeship Publications Ltd.
- [3] Barbhuiya, S.; Das, B. B.; Adak, D. (2024). Roadmap to a net-zero carbon cement sector: Strategies, innovations and policy imperatives. *J. Environ. Manage.*, 359, p. 121052. <https://doi.org/10.1016/J.JENVMAN.2024.121052>
- [4] Oguntola, O.; Boakye, K.; Simske, S. (2024). Towards leveraging artificial intelligence for sustainable cement manufacturing: A systematic review of AI applications in electrical energy consumption optimization. *Sustainability*, 16(11), p. 4798. <https://doi.org/10.3390/su16114798>
- [5] Garcia-Martinez, J. (2021). Chemistry 2030: A roadmap for a new decade. *Angew. Chem. Int. Ed.*, 60(10), pp. 4956–4960. <https://doi.org/10.1002/anie.202014779>

- [6] Sousa, V.; Bogas, J. A. (2021). Comparison of energy consumption and carbon emissions from clinker and recycled cement production. *J. Clean. Prod.*, 306, p. 127277. <https://doi.org/10.1016/J.JCLEPRO.2021.127277>
- [7] Ishak, S. A.; Hashim, H. (2015). Low carbon measures for cement plant – A review. *J. Clean. Prod.*, 103, pp. 260–274. <https://doi.org/10.1016/J.JCLEPRO.2014.11.003>
- [8] Parejo Guzmán, M.; Navarrete Rubia, B.; Mora Peris, P.; Alfalla-Luque, R. (2022). Methodological development for the optimisation of electricity cost in cement factories: The use of artificial intelligence in process variables. *Electr. Eng.*, 104(3), pp. 1681–1696. <https://doi.org/10.1007/s00202-021-01409-z>
- [9] Beguedou, E.; Narra, S.; Afrakoma Armoo, E.; Agboka, K.; Damgou, M. K. (2023). Alternative fuels substitution in cement industries for improved energy efficiency and sustainability. *Energies (Basel)*, 16(8), p. 3533. <https://doi.org/10.3390/en16083533>
- [10] Verma, B.; Padhy, P. K. (2020). Robust fine-tuning of optimal PID controller with guaranteed robustness. *IEEE Trans. Ind. Electron.*, 67(6), pp. 4911–4920. <https://doi.org/10.1109/TIE.2019.2924603>
- [11] Zanolì, S. M.; Pepe, C.; Rocchi, M. (2016). Control and optimization of a cement rotary kiln: A model predictive control approach. In *Indian Control Conference, ICC 2016 - Proceedings*, pp. 111–116. <https://doi.org/10.1109/INDIANCC.2016.7441114>
- [12] Zanolì, S. M.; Pepe, C.; Rocchi, M. (2015). Cement rotary kiln: Constraints handling and optimization via model predictive control techniques. In *Australian Control Conference, AUCC 2015*, pp. 288–293
- [13] Holmblad, L. P.; Ostergaard, J.-J. (1981). Control of a cement kiln by fuzzy logic techniques. *IFAC Control Sci. Technol.*, 14(2), pp. 809–814. [https://doi.org/10.1016/S1474-6670\(17\)63582-1](https://doi.org/10.1016/S1474-6670(17)63582-1)
- [14] Ruby, C. W. (1997). A new approach to expert kiln control. In *IEEE Cement Industry Technical Conference*, pp. 399–412
- [15] Cheng, T. C. E.; Bizruchak, D. (1991). *Expert systems and production/operations management*
- [16] Rodd, M. G.; Verbruggen, H. B.; Krijgsman, A. J. (1992). Artificial intelligence in real-time control. *Eng. Appl. Artif. Intell.*, 5(5), pp. 385–399. [https://doi.org/10.1016/0952-1976\(92\)90010-H](https://doi.org/10.1016/0952-1976(92)90010-H)
- [17] Wang, M.; Chen, E.; Liu, P.; Guo, W. (2020). Multivariable nonlinear predictive control of a clinker sintering system at different working states by combining artificial neural network and autoregressive exogenous. *Adv. Mech. Eng.*, 12(1). <https://doi.org/10.1177/1687814019896509>
- [18] Zhang, Z.; Wu, Z.; Rincon, D.; Christofides, P. D. (2019). Real-time optimization and control of nonlinear processes using machine learning. *Mathematics*, 7(10), p. 890. <https://doi.org/10.3390/MATH7100890>
- [19] D'Avila Garcez, A.; Lamb, L. C. (2023). Neurosymbolic AI: The 3rd wave. *Artif. Intell. Rev.*, 56(11), pp. 12387–12406. <https://doi.org/10.1007/s10462-023-10448-w>
- [20] Pisano, G.; Ciatto, G.; Calegari, R.; Omicini, A. (2020). Neuro-symbolic computation for XAI: Towards a unified model. *CEUR Workshop Proc.*, 2706, pp. 101–117. Accessed Sep. 04, 2024. [Online]. Available: <https://ceur-ws.org>
- [21] Chang, T.-S. (2023). Evaluation of an artificial intelligence project in the software industry based on fuzzy analytic hierarchy process and complex adaptive systems. *J. Enterp. Inf. Manag.*, 36(4), pp. 879–905. <https://doi.org/10.1108/JEIM-02-2022-0056>
- [22] Castillo Tirado, J. L.; Ospina Alarcón, M. A.; Ortiz Valencia, P. A. (2022). Rotary cement kiln: A review of control using expert systems. *Tecnológicas*, 25(55), p. e2391. <https://doi.org/10.22430/22565337.2391>
- [23] Shukla, R. K.; et al. (2024). Applications of alternative fuels with help reduce the cost of cement production. *Eurasian J. Anal. Chem.*, 19(1), pp. 568–574