University of Tehran Press

Industrial Management Journal

Online ISSN: 3115 - 7386

Homepage: https://imj.ut.ac.ir

Smart Maintenance in the Cement Industry: A Meta-Synthesis of Industry 4.0 Technologies and Applications

Mohadese Bourghani Farahani [1], **Rohollah Ghasemi** ✉ [2], **Ali Mohaghar** [3], **and Arzhang Khoshghalb** [4]

1. M.Sc. Student of Production and Operations Management, Faculty of Industrial Management and Technology, College of Management, University of Tehran, Tehran, Iran. E-mail: mohi.farahani@ut.ac.ir
2. Corresponding author, Assistant Prof., Faculty of Industrial Management & Technology, College of Management, University of Tehran, Tehran, Iran. E-mail: ghasemir@ut.ac.ir
3. Prof., Faculty of Industrial Management & Technology, College of Management, University of Tehran, Tehran, Iran. E-mail: amohaghar@ut.ac.ir
4. MSc. of Supply Chain Management , Department of Logistics and Operations, Business School, HEC Montreal University, Quebec, Canada. E-mail: arzhang.khoshghalb@hec.ca

Article Info

Article type:
Research Article

Article history:
Received January 07, 2026
Received in revised form February 09, 2026
Accepted March 12, 2026
Available online April 01, 2026

Keywords:
Intelligent maintenance, cement industry, industrial 4.0 technologies, meta-synthesis.

ABSTRACT

Objective: The cement industry, vital to infrastructure and the economy, faces challenges such as high energy use, significant environmental emissions (nearly a ton per ton of cement), high costs, and unplanned downtime. Traditional maintenance methods are often inefficient and costly. Transitioning to Smart Maintenance—using Industry 4.0 data-driven, predictive, and prescriptive strategies—is essential for survival. It aims to boost efficiency, reduce costs, improve safety, and meet sustainability goals by optimizing energy and materials, making industries more resilient, agile, and future-ready, and future-proofing industrial operations. This research aims to identify, categorize, and explain key Industry 4.0 technologies and their practical applications in smart maintenance of the cement industry. It addresses a gap by providing a structured framework that links these digital technologies to specific maintenance functions, offering clarity for academia and industry in this slow-to-innovate sector.

Methodology: This study used a rigorous qualitative meta-synthesis to review and synthesize literature, conducting a protocol-driven search across Scopus and Web of Science for peer-reviewed articles from 2020 to 2025. After a multi-stage screening and quality assessment with CASP, 36 high-quality articles were selected. Through inductive coding and thematic synthesis, core technologies and applications were systematically extracted, analyzed, and categorized.

Results: The meta-synthesis identified 8 key Industry 4.0 technologies for smart maintenance, with 27 applications. These include IoT with 5 applications; Robotics and Drones with 4; and AI & Machine Learning, Digital Twin, AR/VR, Blockchain, Edge & Cloud Computing, and 3D Printing, each with 3 applications. They cover the entire maintenance lifecycle, from predictive analytics and virtual stress simulation to automated inspections, real-time monitoring, blockchain record-keeping, and 3D printing for spare parts.

Conclusion: This study provides a validated, structured framework that maps the Industry 4.0 ecosystem to smart maintenance in the cement sector. It offers a clear roadmap for stakeholders from plant managers to executives to shift from reactive to proactive, intelligent asset management. The framework guides technological investments and creates a taxonomy for further research. Future studies can explore implementation, ROI, integration, and sustainability impacts, helping the industry achieve resilience, productivity, and environmental goals.

Cite this article: Bourghani Farahani, M., Ghasemi, R., Mohaghar, A. & Khoshghalb, A., (2026). Smart maintenance in the cement industry: A meta-synthesis of industry 4.0 technologies and applications, ***Industrial Management Journal***, 18(2), 101-125. https://doi.org/10.22059/imj.2026.408275.1008276

Publisher: University of Tehran Press.

DOI: https://doi.org/10.22059/imj.2026.408275.1008276

Introduction

As a cornerstone of global economic infrastructure and construction project execution, the cement industry holds fundamental importance (Mahmood et al., 2024). Within the Iranian context, this sector serves as a pivotal nexus connecting infrastructural advancement with economic expansion. Its continued status as a leading regional producer and exporter presents a strategic opportunity to pioneer and integrate intelligent solutions that foster sustainable production. Notwithstanding this potential, the industry faces a range of persistent and significant challenges, including excessive energy consumption, significant environmental pollution, elevated operational expenditures, and disruptive unplanned production stoppages (Tong et al., 2023).

Conventional maintenance paradigms employed within this sector have demonstrated considerable limitations. Research indicates that these traditional approaches are not only suboptimal but may also render up to half of all preventive maintenance activities ineffective. This inefficiency precipitates a cascade of adverse outcomes, including a higher frequency of emergency failures, diminished overall productivity, and reduced operational lifespan of critical equipment (Rosati et al., 2023). This process accounts for approximately 15% of total industrial energy consumption, and the production of each ton of cement concurrently emits between 0.73 and 0.99 tons of carbon dioxide into the atmosphere (Mokhtar & Nasooti, 2020).

The advent of technologies characterizing the Fourth Industrial Revolution (such as the Industrial Internet of Things (IIoT), Artificial Intelligence (AI), Digital Twin, and Big Data analytics, has precipitated a fundamental paradigm shift in maintenance methodologies (Pinciroli et al., 2023). The deployment of predictive maintenance strategies, powered by smart sensors and sophisticated machine learning algorithms, now facilitates the early identification of potential faults. Concurrently, Digital Twin technology enables the creation of high-fidelity process simulations, allowing engineering teams to rigorously test and validate corrective measures in a virtual environment before physical implementation, thereby preventing actual failures.

While the transformative benefits of Industry 4.0 technologies are widely acknowledged in the literature, extant research has predominantly concentrated on either technical implementation details or broad sustainability analyses. A conspicuous gap persists in the form of a holistic, systematic examination that identifies explicitly, analyzes, and categorizes these emerging technologies and their practical applications in the sphere of intelligent maintenance for the cement industry. The absence of such a consolidated, structured study is keenly felt.

This identified research lacuna substantiates the critical necessity for a dedicated meta-synthesis study. The primary objective of such an inquiry is to systematically identify, analyze, and categorize the suite of Industry 4.0 technologies and their specific applications relevant to intelligent maintenance in cement manufacturing. To guide this investigation, the present study is framed by the following core research questions:

1. What are the principal Industry 4.0 technologies applicable to maintenance operations in cement manufacturing companies?
2. What are the specific applications of these technologies, and how can they be systematically categorized?

Addressing these questions through a rigorous meta-synthesis can yield a clear and actionable framework. Such a framework would provide industry managers and decision-makers with a vital roadmap for the strategic adoption and successful implementation of Industry 4.0 technologies. Consequently, this endeavor represents a significant step toward achieving key sustainability objectives in this strategic industry, with anticipated outcomes including a marked reduction in operational costs, enhanced productivity, and fewer unplanned production line stoppages.

Literature Background

The cement sector, a foundational pillar of industrial activity, perennially faces significant operational hurdles. These encompass exorbitant energy requirements, substantial operational expenditures, and the disruptive impact of unscheduled production halts (Tong et al., 2023). Historically, maintenance regimes within this industry have been predominantly anchored in conventional reactive and scheduled methodologies. Such approaches are frequently characterized by inefficiency and elevated cost structures. Research by Rosati et al. (2023) underscores this inefficiency, suggesting that traditional practices may render up to 50 percent of preventive maintenance efforts ineffective. The emergence of the Fourth Industrial Revolution (Industry 4.0) paradigm, however, has catalyzed new opportunities for profound transformation in asset management and maintenance protocols across capital-intensive sectors such as cement production. This section of the literature review delineates the core concepts, overarching developments, and practical instantiations of intelligent maintenance as enabled by the Industry 4.0 framework within this specific industrial context.

Transition to Intelligent Maintenance

Intelligent maintenance can be conceptualized as a sophisticated approach that employs advanced, data-driven artificial intelligence technologies to sustain the operational health and reliability of machinery and critical infrastructure (Bokrantz et al., 2020). In stark contrast to traditional methodologies that depended heavily on experiential knowledge and intuition, this modern paradigm leverages real-time data streams and sophisticated analytical tools. This enables far more precise maintenance scheduling and facilitates the proactive prediction of potential failures. Bokrantz and Skoogh (2023) observe that the pervasive trend of digitalization has fundamentally redefined maintenance, elevating it from a peripheral support function to a core strategic operation deeply integrated with production objectives. The paramount value of these intelligent systems, therefore, resides not merely in the aggregation of data but in its strategic utilization to inform and optimize the entire maintenance decision-making cycle.

Developments of the Fourth Industrial Revolution in the Cement Industry

Industry 4.0, or the Fourth Industrial Revolution, is fundamentally predicated on the seamless integration of digital technologies to facilitate real-time data acquisition and subsequent analysis (Lee et al., 2015). Its central tenet is smart manufacturing—a highly adaptive production ecosystem featuring flexible lines that can autonomously adjust processes in response to fluctuating conditions (Wang et al., 2016). Within the cement industry, this transformative shift manifests as a comprehensive process of "digitalization." This entails the strategic integration of novel technologies—including the Internet of Things (IoT), Cyber-Physical Systems (CPS), cloud computing, and cognitive computing—with established cement manufacturing processes (Andronie et al., 2021).

The principal objectives driving this digital transformation are multifaceted: enhancing productivity, elevating product quality, curtailing costs, and advancing toward sustainable production models. Empirical evidence suggests, for instance, that implementing Advanced Process Control (APC) technologies coupled with integrated information platforms can yield energy savings of 2 to 5 percent while reducing labor requirements by approximately 20 percent (Pepe et al., 2025). For example, a case study by Ammar et al. (2022) demonstrates that the synergistic integration of Industry 4.0 principles with a Reliability-Centered Maintenance (RCM) strategy at a cement production facility led to measurable improvements, including increased production volumes, reduced downtime, and enhanced environmental performance metrics.

While Industry 4.0 technologies are applied across various facets of cement manufacturing, their specific deployment in the maintenance domain is particularly relevant to this study. The subsequent sections of this paper will systematically identify and categorize these applications through a meta-synthesis methodology. In summation, the extant literature unequivocally indicates that the Fourth Industrial Revolution, through the introduction of transformative technologies such as IoT, AI, Digital Twin, and Robotics, is actively reshaping the traditional maintenance paradigm in cement production. The strategic shift from reactive models to predictive and preventive frameworks not only promises reduced operational costs and improved equipment availability but also plays a critical role in helping the industry achieve its sustainability ambitions by optimizing the consumption of energy and material resources. It is crucial to note, however, that the successful deployment of these technologies necessitates a holistic approach that concurrently addresses technical, human, and organizational dimensions. This review thus establishes the essential conceptual foundation for a deeper understanding of advancements in intelligent maintenance within the cement industry. It will serve as the basis for a more nuanced analysis of the findings of the present research.

Materials and Methods

This study adopts a qualitative research approach, grounded in interpretive-critical paradigms. This foundational perspective is particularly suited to investigating the more nuanced and less overt dimensions of complex phenomena. In alignment with this philosophical stance, the research is classified as "descriptive-applied" in its ultimate purpose and as qualitative in nature with respect to both the primary and secondary data used. The initial phase of the inquiry was prompted by the observation of a discernible gap in the existing literature: a comprehensive model detailing the dimensions of process intelligence within supply chain contexts. Consequently, a preliminary investigation was conducted to elucidate the intricacies of these relational dimensions.

To execute this research and systematically extract the constituent components influencing the "intelligentization of maintenance in the cement industry," the meta-synthesis methodology was selected and implemented. The process commenced with the formulation of a rigorous strategy to guide the systematic search for and selection of pertinent scholarly articles. Subsequently, a defined corpus of literature was assembled by extracting relevant publications from reputable scientific databases, focusing on the 2020-2025 timeframe (the most recent 6-year period). Following an initial refinement of the gathered articles, an in-depth content analysis was conducted on 61 articles, using the structured procedures inherent to the meta-synthesis method.

The meta-synthesis method is distinguished by its capacity to provide a systemic, overarching perspective by synthesizing findings from multiple qualitative studies. Its principal aim is to uncover novel, fundamental themes and conceptual metaphors that may not be apparent in individual studies alone. By synthesizing and elevating discrete qualitative findings, this approach facilitates the development of a more comprehensive and expansive framework for examining multifaceted issues (Mohaghar et al., 2013). A core strength of meta-synthesis lies in its integrative function; it amalgamates research outcomes in a manner that yields added value beyond the mere aggregation of individual study results, thereby generating novel insights unattainable through the examination of any single study in isolation (Crowe et al., 2017). The overarching objective of this methodological approach is thus to meticulously scrutinize, critically evaluate, and coherently synthesize a body of research to arrive at a new, integrative pattern or model (Hall et al., 2017). The procedural execution of this research adhered to an established seven-step meta-synthesis protocol, as visually outlined in Figure 1.

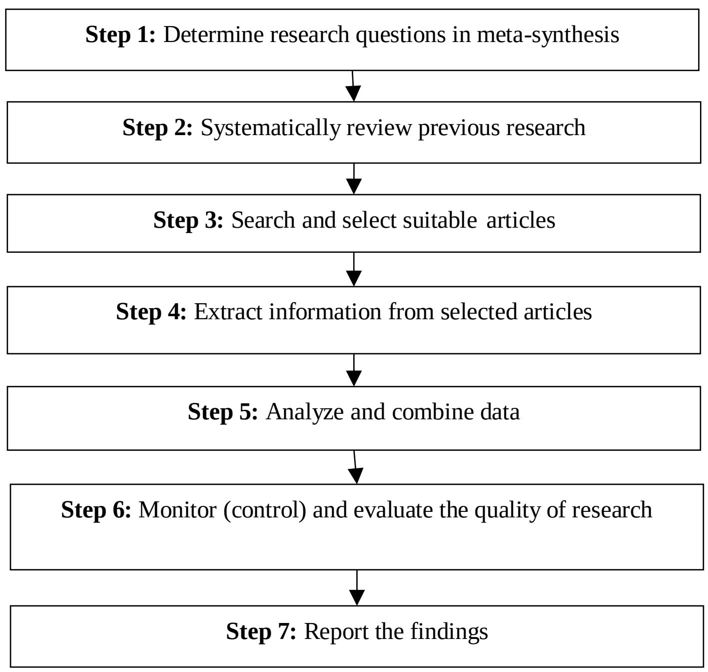

Figure 1. Seven steps of the meta-synthesis method (Sadlowski & Barroso, 2007)

The meta-synthesis methodology encompasses a spectrum of both established and evolving analytical approaches. Its fundamental principle involves integrating reviews from disparate studies to construct a broader, more synthesized conceptual understanding, thereby yielding findings with direct relevance and applicability to practical contexts (Paterson et al., 2009). For the operational implementation of this study, the structured seven-step methodological framework developed by Sandelowski and Barroso (2006) was employed (as cited in Finfgeld-Connett, 2018). This rigorous framework, through its systematic procedure for synthesizing qualitative research, serves a dual critical function. It not only contributes to the augmentation and deepening of extant knowledge within the field but also furnishes a holistic and thorough foundation of insight essential for the practical analysis and resolution of complex research problems (Mohaghar et al., 2022).

Results

Based on the steps of the meta-synthesis method, the research findings were obtained as follows:

Step One: Formulating the Research Question

In this stage, the basic research questions were formulated, delineating the study's scope and clarifying subsequent steps (Adler & Lalonde, 2020). The main research question was defined as follows: "What are the factors affecting the intelligentization of maintenance within the framework of Industry 4.0 in the cement industry based on research published in reputable international journals and databases (in English) from 2020 to 2025, and how can they be grouped?" This question was structured into four parts:

- **What:** Identifying, categorizing, and grouping Industry 4.0 technologies and their applications in the intelligent maintenance of the cement industry.
- **Who:** The statistical population consisting of research in the field of maintenance intelligentization in the cement industry.
- **When:** The time period from 2020 to 2025.
- **How:** Using previous texts and articles as secondary data.

Second Step: Systematic Review of Previous Research

In this step, using the strategies specified in Table 1, a systematic review of reputable academic books, publications, and articles from reputable journals and scientific databases was conducted.

Table 1. Results of Systematic Search of Books and Articles Related to Research Strategies

Title	Acceptance Criteria
Study Time	(April-October 2025)
Time Scope of Source Search	From 2020 to 2025 (the last 6 years)
Language of Research	English
Type of Articles	Articles published in reputable scientific journals and international conferences
Method of Studies	Qualitative data collection method, data analysis, and review of quantitative results
Geographical Scope	International Research
Studied Topics	Intelligentization, Intelligent Maintenance, Cement Industry, Industry 4.0, Emerging Technologies, Transformational Technologies
Statistical Population	Scientific databases: Scopus and Web of Science
Studied Statistical Population	Cement industry and its supply chain

Therefore, the criteria of Table 3 for organizing the review of books and articles, based on the keywords in Table 4 with the help of the AND operator simultaneously with the terms "Maintenance," "Intelligentization," and "Cement Industry," were searched:

Table 2. Search Keywords

Selected Keywords
Intelligence
Maintenance
Cement Industry
Industry 4.0
Emerging Technologies
Transformational Technologies

Step Three: Searching for and Selecting Suitable Articles

In the third step of the research, titled 'searching for and selecting suitable articles,' the screening and evaluation of articles were carried out with great care. In this stage, articles that did not meet the necessary conditions were removed from the meta-synthesis process based on title, inclusion and exclusion criteria, and abstract content. When suitable articles reached the final review stage, i.e., full-text review, the researcher used critical appraisal tools to assess the quality of the remaining articles and select the final set by eliminating irrelevant articles (Chen et al., 2020). Considering the specified keywords and using the AND operator among the key terms "Maintenance," "Intelligentization," and "Cement Industry," a total of 214 articles were identified. Then, through careful review and evaluation of the articles' content, research methods, and alignment with the research objectives, irrelevant articles were removed.

At the first level, articles were reviewed based on the title. At the second level, articles and books were evaluated based on abstract content, and works lacking the necessary alignment were removed. At the third level, the full content of articles and books was analyzed, and works not relevant to the main research question were excluded. At the end of these stages, the final number of remaining articles and books that were related to the research method and aligned with the content of intelligentization in the field of intelligent maintenance was determined and specified.

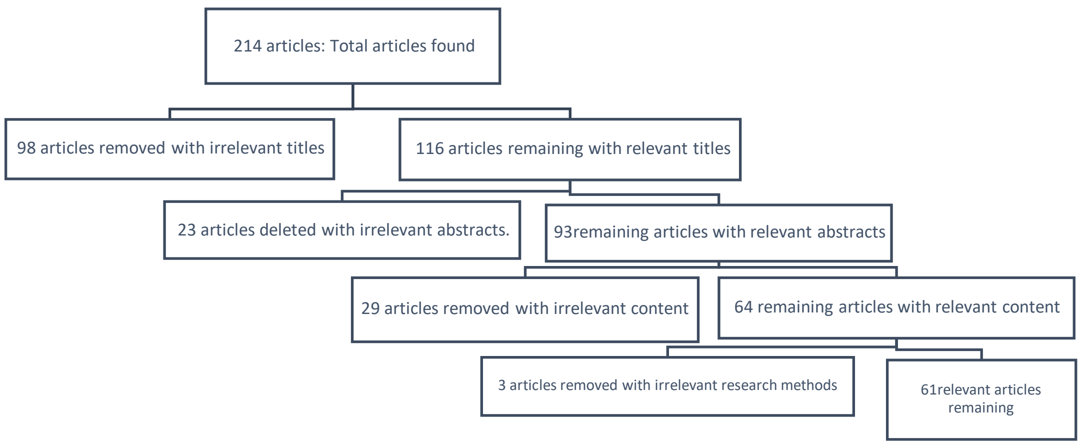

Figure 2. Summary of the books' and articles' search and selection process (Meta-Synthesis Diagram)

In the fourth research step, titled "Qualitative Evaluation of Final Articles," the "Critical Appraisal Skills Programme (CASP)" method was used. Accordingly, each article was evaluated based on 10 qualitative criteria. This tool helps the researcher examine articles from various perspectives on accuracy, validity, and content quality. Scoring for each article was done on a scale of 1 to 5. According to Table 3, articles that receive at least 30 points and have their quality confirmed will remain on the final list, while the rest will be removed (Mohaghar et al., 2024).

The "Critical Appraisal Skills Programme (CASP)" method in this research considers the following conditions: “(1) alignment of the reviewed article’s objectives with the core research goals; (2) currency and appropriateness of the research method, (3) study design; (4) suitability of the sampling approach; (5) quality and reliability of the data collection techniques; (6) generalizability of findings beyond the study context; (7) thoroughness in adhering to relevant ethical considerations; (8) precision in data analysis, confirming methodological rigor; (9) clarity and transparency in the presentation of results; and (10) the overall significance and contribution of the article" will be considered (Mohaghar et al., 2024).

In this process, the research team assigned a quantitative score of 1-5 to each of the 10 criteria, and the total score for each article was capped at 50. Articles that scored less than 30 were removed, and the other articles entered the final analysis stage (Daneshjoovash et al., 2020). The selection of a minimum threshold of 30 points (60% retention) is directly rooted in the foundational application of the CASP framework, as established in the core literature used to validate this appraisal process [e.g., (Mohaghar et al., 2024)]. This 30/50 benchmark is not arbitrary but rather represents the established standard for distinguishing studies with sufficient methodological soundness and acceptable quality for inclusion in a high-level meta-synthesis.

The classification of articles will be done overall after scoring and summarizing each article in the ten dimensions, as can be seen in Table 3:

Table 3. Article Scoring System

Article Classification	Very Poor	Poor	Moderate	Good	Very Good
Score Range	0-10	11-20	21-30	31-40	41-50

Based on the evaluation presented in Table 6, of the 61 reviewed articles, 15 with scores below 30 were removed from the study, and 36 were ultimately confirmed as eligible for final analysis.

Table 4. Scores of 36 valid articles out of 61 reviewed articles using CASP

Authors (Year)	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10	Article Score
(Fatahi et al., 2025a)	5	5	3	4	3	5	4	5	4	3	41
(Oguntola et al., 2025)	4	4	4	3	5	4	3	3	5	5	42
Yin et al., (2025)	4	4	3	5	3	5	3	5	4	4	40
(Gorski et al., 2025)	4	5	3	5	5	3	3	4	5	5	42
(Zheng et al., 2025)	5	3	4	5	4	3	5	3	5	5	42
(Dai et al., 2025)	5	4	5	4	4	4	5	5	4	5	45
(D. Lee et al., 2025)	4	5	3	4	5	5	3	5	3	5	42
(Villarino et al., 2025)	4	5	4	3	5	5	4	4	5	5	44
(Han et al., 2025a)	4	5	4	3	5	5	4	3	3	5	41
(Rojas et al., 2025)	5	3	5	3	5	5	4	5	3	5	43
(Raju Arvind et al., 2025)	5	4	5	3	5	4	5	4	5	3	43
(Y. Wang et al., 2024)	4	5	5	3	5	4	3	5	3	4	41
(Oguntola et al., 2024c)	5	3	5	5	3	5	4	3	4	4	41

Authors (Year)	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10	Article Score
(Ciancio et al.,2024.)	4	5	4	4	5	3	5	5	4	5	44
(Tortorella et al., 2024)	4	3	5	5	4	5	3	4	3	4	40
(K. Zhang et al., 2024)	4	3	5	4	5	3	3	5	3	4	39
(R. Guo et al., 2024)	5	4	5	4	3	5	4	4	5	4	43
(Fan et al., 2023)	4	5	3	4	5	3	4	3	4	5	40
(Müller et al., 2023)	5	4	4	5	3	5	4	5	3	5	43
(H. Liu et al., 2023)	5	3	4	3	5	5	5	4	5	5	44
(Ramzey et al., 2023)	5	4	5	3	3	5	3	4	5	3	40
(Slama et al., 2023)	5	4	5	3	4	5	3	5	3	4	41
(Roscoe et al., 2023)	4	4	5	3	5	4	3	5	3	5	42
(Dabek et al., 2022)	3	5	3	4	3	5	4	3	5	4	39
(Checa et al., 2022)	3	5	4	3	5	5	3	5	5	4	42
(Congress & Puppala, 2022)	5	4	5	5	4	4	4	4	5	5	45
(Lekidis et al., 2022)	3	5	4	5	3	5	4	3	4	4	40
(Miličević et al., 2022)	3	5	3	4	3	5	5	3	4	5	42
(Sahara & Aamer, 2022)	4	3	4	5	3	5	4	5	3	4	40
(Truong et al., 2022)	4	4	3	3	3	3	3	4	5	4	36
(Seki et al., 2021)	5	5	3	3	3	3	4	3	5	4	38
(Branding & Abrishami, 2021)	4	4	5	5	3	5	3	5	4	5	43
(Kumar, R. 2021)	4	5	3	5	5	3	4	5	3	4	41
(Barata et al., 2020)	5	3	5	5	3	5	5	4	5	4	44
(Y. Wang et al., 2024)	4	5	5	3	5	4	3	5	3	4	41
(Oguntola et al., 2024c)	5	3	5	5	3	5	4	3	4	4	41
(Ciancio et al.,2024.)	4	5	4	4	5	3	5	5	4	5	44
(Fatahi et al., 2025a)	5	5	3	4	3	5	4	5	4	3	41
(Oguntola et al., 2025)	4	4	4	3	5	4	3	3	5	5	42
(Yin et al., 2025)	4	4	3	5	3	5	3	5	4	4	40
(Gorski et al., 2025)	4	5	3	5	5	3	3	4	5	5	42
(Zheng et al., 2025)	4	3	4	5	4	3	5	3	5	5	42
(Dai et al., 2025)	5	4	5	4	4	4	5	5	4	5	45
(D. Lee et al., 2025)	4	5	3	4	5	5	3	5	3	5	42
(Villarino et al., 2025)	4	5	4	3	5	5	4	4	5	5	44
(Han et al., 2025a)	4	5	4	3	5	5	4	3	3	5	41
(Rojas et al., 2025)	5	3	5	3	5	5	4	5	3	5	43
(Raju Arvind et al., 2025)	5	4	5	3	5	4	5	4	5	3	43

Fourth Step: Extracting Information from Selected Articles

In the fourth step of the research, titled "Extracting Information from Selected Articles," a standardized "Checklist" was employed to extract the findings of the selected articles systematically. This checklist included items such as researchers' names, publication year, journal title, and key research findings (Zhang & Xiao, 2020). In this stage, the final articles were examined against the criterion of addressing the questions defined in the initial step, and coding was performed using the "Checklist." The "Checklist" used covered essential dimensions, including article code, year of publication, authors' names, and findings related to technologies and applications of intelligent maintenance in the cement industry. In the fourth step, 27 open codes (sub-codes) were identified as technological applications under 8 technologies, along with their sources. It is worth noting that the results from steps four and five are summarized together in Table 5.

Fifth Step: Data Analysis and Synthesis

In the fifth step of meta-synthesis, the researcher aims to create an integrated and comprehensive perspective by categorizing, coding, and synthesizing the findings of the selected articles (Lazazzara et al., 2020; Daneshjoovash et al., 2020). In this stage, open (sub)codes with similar meanings are merged, and final subcodes with conceptual and applicational commonalities are categorized into single categories. Finally, core codes (themes) are extracted, and the commonalities of sub-codes are displayed in Table 5. The results of steps four and five are summarized in the table below.

Table 5. Coding results

Axial code	Commonality of Open Codes	Open code	Application Explanation	Source
Artificial Intelligence and Machine Learning	The commonality across all these applications is "predicting and preventing failures through real-time and historical data analysis to optimize decision-making in maintenance" within the framework of AI and Machine Learning.	Predicting Remaining Useful Life (RUL) of Equipment	Analyzing sensor data to predict the precise replacement time for critical components such as bearings or conveyor belts.	(Y. Wang et al., 2024)
		Automatic Detection of Failure Patterns	Identifying abnormal patterns in vibration and thermal data that indicate the onset of a fault.	(Fatahi et al., 2025a)
		Optimizing Maintenance Schedule	Automatically prioritizing repair requests based on failure severity, parts availability, and impact on the production line.	(Oguntola et al., 2024c)
Digital Twin	Using a dynamic and synchronous digital model with the real world to	Simulating Equipment Stress and Fatigue	Digital modeling of a component (e.g., pump rotor) under	(Oguntola et al., 2025)

Axial code	Commonality of Open Codes	Open code	Application Explanation	Source
	simulate, predict, and optimize performance before taking physical action or failure occurrence.		real operational loads to predict potential failure points and plan for localized inspections.	
		Virtual Testing of Repair Solutions	Before implementing a major repair (e.g., replacing a shaft), its impacts and validation are tested in the digital model to prevent errors in the real world.	(Dai et al., 2025; W. Yin et al., 2025)
		Virtual Calibration and Adjustment of Systems	Adjusting the parameters of a control system, such as a PID controller, in the digital model to achieve optimal performance, and then applying those settings to the physical system.	(Han et al., 2025a)
Augmented Reality and Virtual Reality	Increasing productivity, accuracy, and safety in maintenance processes by integrating digital information with the real physical environment or a simulated one.	Displaying Repair Instructions Live on Equipment	Overlaying graphical steps for disassembly, troubleshooting, and assembly of a device onto the technician's real-world view.	(Fan et al., 2023)
		Practical and Safe Training of Repair Personnel in a VR Environment	Simulating complex failures and practicing repair methods without risk to personnel or equipment.	(Checa et al., 2022; F. Gorski et al., 2025)
		Remote Support from Experts	Sharing the technician's live view with an expert elsewhere in the world and receiving visual guidance.	(Müller et al., 2023)
Blockchain	Creating transparency, trust, and automation in maintenance processes through decentralized, immutable, and	Tracking Authenticity and History of Spare Parts	Immutably recording production, purchase, and maintenance information for each part to combat counterfeit parts.	(Branding & Abrishami, 2021)
		Transparent Recording of Maintenance Logs	Creating a permanent and reliable record	(Miličević et al., 2022)

Axial code	Commonality of Open Codes	Open code	Application Explanation	Source
	traceable recording of information.		for each device that includes all maintenance actions, part replacements, and responsible personnel.	
		Automating Smart Contracts with Suppliers	Automatic payment after successful completion of a repair service by an external contractor.	(H. Liu et al., 2023)
Edge and Cloud Computing	Optimizing data management and information processing through intelligent distribution of computational resources between edge and cloud to achieve fast response, deep analysis, and ubiquitous access.	Storing and Processing Massive Sensor Data	Creating a complete history of equipment performance for long-term analysis and identifying wear trends.	(Ciancio et al.,2024)
		Real-time Processing of Critical Data at the Edge	Immediate detection of dangerous conditions (such as sudden temperature rise) and triggering alerts without the delay of sending data to the cloud.	(Ramzey et al., 2023)
		Secure Remote Access to Maintenance Management Software	Enabling technical teams to monitor and plan maintenance from any location.	(Barata et al., 2020; Tortorella et al., 2024)
Robotics and Drones	Replacing or assisting human labor in performing high-risk, inaccessible, or repetitive tasks in industrial environments, aiming to increase the safety, accuracy, and efficiency of inspection and repair operations.	Automated Inspection of Hazardous Environments	Using crawler robots to inspect tanks, chimneys, or pressurized pipelines.	(Zheng et al., 2025)
		Performing Primary Repairs in Inaccessible Locations	Using robotic arms for welding, sanding, or tightening connections in confined spaces.	(D. Lee et al., 2025; Seki et al., 2021)
		Collecting Visual and Thermal Data	Automated scanning of equipment surfaces to identify cracks, corrosion, or hot spots.	(Dabek et al., 2022; K. Zhang et al., 2024)
		Inspecting Confined, Elevated, and Hazardous Environments with Drones	Using climber robots and drones for visual inspection, thermography, and dimensional measurement of	(Congress & Puppala, 2022; Lekidis et al., 2022; Villarino et al., 2025)

Axial code	Commonality of Open Codes	Open code	Application Explanation	Source
			internal and external surfaces.	
3D Printing	Reducing equipment downtime and increasing flexibility in the maintenance process through rapid, customized, and on-demand production of parts, tools, and prototypes on-site.	Rapid Production of Obsolete or Custom-designed Spare Parts	Eliminating long wait times for ordering rare parts.	(Kumar, R. 2021).
		Fabricating Custom Repair Tools and Fixtures	Rapidly designing and printing the tools needed to repair a specific device.	(Slama et al., 2023)
		Producing Prototypes for Testing Repair Solutions	Virtual testing of a new part before its final production.	(Roscoe et al., 2023)
Internet of Things (IoT)	Creating a comprehensive and real-time view of equipment and asset health through an integrated network of sensors and intelligent systems for prediction, monitoring, and optimal management of maintenance processes.	Smart Tracking of Spare Parts and Management of Physical Assets	Example: Installing RFID tags or IoT sensors on critical spare parts (such as large bearings, kiln rollers, high-pressure motors).	(Sahara & Aamer, 2022)
		Monitoring the Condition of Thermal Insulation	Installing temperature sensors embedded within the refractory layers of rotary kilns and preheaters.	(Rojas et al., 2025)
		Monitoring Storage Conditions of Spare Parts	Example: Using IoT sensors to monitor environmental conditions in spare parts warehouses.	(Raju Arvind et al., 2025)
		Intelligent Alert System for Sensitive Equipment	Example: Implementing anomaly detection algorithms on IoT data.	(Truong et al., 2022)
		High-Precision Mechanical Performance Monitoring	Using Acoustic Emission (AE) or high-frequency vibration sensors.	(R. Guo et al., 2024)

While the identified eight technologies are recognized within the broader Industry 4.0 discourse, the core novelty and primary contribution of this meta-synthesis reside in the empirical specification and domain-specific translation demonstrated across the 27 extracted applications. Unlike generalized reviews, our findings are rigorously filtered through the lens of the cement sector’s unique operational constraints and capital-intensive assets. For instance, generic RUL prediction (AI/ML) is used to predict the failure of a Rotary Kiln's bearing, and generic data storage (Edge/Cloud) is anchored to long-term trend analysis of refractory insulation performance (IoT). This systematic mapping, explicitly detailed in the "Application Explanation" column of Table 5, elevates the work from a mere taxonomy of technologies to a validated, actionable blueprint for intelligent maintenance within the specific context of cement manufacturing, thereby directly addressing the gap concerning industry-specific contribution.

Table 6. Classification results

Technologies	Number of Open Codes (Subcategories)
Artificial Intelligence and Machine Learning	3
Digital Twin	3
Augmented Reality and Virtual Reality	3
Blockchain	3
Edge and Cloud Computing	3
Robotics and Drones	4
3D Printing	3
Internet of Things (IoT)	5

While Table 6 provides the necessary taxonomy, classifying the 27 applications across 8 core technologies, our analysis in the Discussion section elevates this beyond mere description. We move toward a critical synthesis by mapping the interactions and dependencies among these technological clusters. For instance, we implicitly structure a pathway for adoption: foundational data acquisition via IoT and Edge Computing is a prerequisite for the prescriptive modeling power of AI/ML and Digital Twin technologies. This articulation of capability sequencing, detailed in the Discussion, serves as our contribution to implicit prioritization, guiding practitioners in establishing an integrated technological roadmap rather than isolated technology deployment. This research's scope intentionally incorporates technologies initially developed for general industrial applications (e.g., AI for fault prediction, IoT for asset tracking) and synthesizes their utility specifically for the cement sector. As demonstrated by the distribution in Table 5, where findings are derived from cross-sectoral relevance, this 'translation philosophy' justifies the inclusion of non-cement-specific literature by confirming that the underlying technological mechanism (e.g., anomaly detection algorithms) is directly transferable to the unique operational challenges identified in our focused review.

Notwithstanding its contributions, this research is subject to certain limitations that must be acknowledged. Primarily, while it charts the technological landscape, it does not explicitly address the profound contextual challenges of implementing these solutions within the specific operational environment of Iranian cement companies. The industry faces unique and severe constraints stemming from international sanctions, notably intensified by geopolitical events in the first half of 2025. These sanctions critically impede access to advanced hardware, proprietary software, genuine spare parts, and international technical support, thereby exponentially inflating costs and risks. Compounding these external barriers are internal challenges, such as constrained technology-transfer mechanisms and foundational gaps in the necessary digital infrastructure. A second key limitation is the study's primary focus on the "what" rather than the "how" of implementation, as it does not provide a phased technological roadmap or a decision-making framework for prioritizing technologies based on variables like local resource availability or organizational readiness under constrained conditions, which can lead to misallocation of scarce resources.

Sixth Step: Monitoring and Evaluating Research Quality

In the sixth step titled "Monitoring and Evaluating Research Quality," the primary focus was on the internal validation of the research. Using the "Critical Appraisal Skills Programme (CASP)" method, the studies' content was qualitatively evaluated, and the inter-coder agreement method was used to assess the model's reliability (Horton, 2020; Cheng & Bai, 2022). To calculate reliability, 61 articles were randomly selected and reviewed by an expert in the field of intelligentization. Of the 43 codes extracted by the two researchers, Cohen's Kappa coefficient was 75.32%, indicating acceptable agreement between the coders. These results signify the desirable quality of the extracted concepts. All actions in this stage were taken to ensure the accuracy of the research execution and the systematic extraction of concepts related to the research topic.

Step Seven: Presenting the Findings

In this step, the results from the previous stages were systematically followed up on, and the outcomes were presented as a model. The framework was presented in Table 6 and Figure 3, and the results were validated through a survey in collaboration with 3 experts, and these experts approved the overall proposed model:

Figure 3. Components and Categories of Intelligentization of Maintenance in the Cement Industry

Discussion

This study has employed a systematic meta-synthesis approach to identify, delineate, and categorize the pivotal Industry 4.0 technologies and their specific practical applications in the sphere of intelligent maintenance for the cement industry. The analytical synthesis yielded a framework of eight core technologies generating 27 distinct applications. This portfolio includes the Internet of Things (IoT) with five applications, Robotics and Drones with four, and six additional technologies—Digital Twin, Augmented and Virtual Reality, 3D Printing, Edge and

Cloud Computing, Blockchain, and Artificial Intelligence & Machine Learning—each contributing three applications. This consolidated view substantiates and extends the assertions of prior research, such as that by Rosati et al. (2023) and Pinciroli et al. (2023), which broadly highlighted the transformative potential of digitalization in shifting maintenance from a reactive to a predictive paradigm. The present research, however, advances the discourse by moving beyond general affirmations of transformation. It provides a meticulously structured taxonomy that concretizes how each technology translates into actionable maintenance functions. This systematic classification represents a significant scholarly contribution, offering a more granular and comprehensive “capability map” for stakeholders. By elucidating specific operational applications—such as AI-driven prediction of remaining useful life (RUL), Digital Twin-enabled simulation of equipment stress, and robotic automation of hazardous inspections—this study vividly illustrates the direct mechanistic pathways through which these technologies can optimize costs, bolster productivity, and advance sustainability objectives, thereby bridging the gap between high-level technological promise and practical, on-the-ground implementation.

The primary innovation of this work lies in its integrative and clarifying framework. While previous literature often examined technologies in isolation or focused on singular case studies, this meta-synthesis provides a holistic landscape, revealing the synergistic potential of a technological ecosystem. It demonstrates that the value of Industry 4.0 in maintenance is not monolithic but arises from a combination of capabilities: from data acquisition (IoT) and processing (AI, Edge Computing) to simulation (Digital Twin), execution (Robotics, 3D Printing), and governance (Blockchain). This structured mapping is a critical step towards developing a coherent implementation strategy, addressing a noted gap in research that has often prioritized technical feasibility over structured adoption roadmaps.

Conclusion

This study has undertaken a critical systematic synthesis, successfully mapping the ecosystem of Industry 4.0 technologies and their specific applications for intelligent maintenance within the cement industry. By identifying and categorizing eight core technologies and 27 distinct applications, the research provides a foundational framework that moves the discourse from abstract potential to concrete functional capabilities. This structured taxonomy not only validates the transformative narrative of digitalization but also offers industry stakeholders a clear inventory of tools to enhance predictive analytics, automate hazardous tasks, optimize resource use, and improve decision-making transparency. However, translating this technological map into tangible operational and strategic value, particularly in challenging contexts such as Iran’s industrial landscape, poses a multifaceted challenge that extends beyond technical feasibility. The successful realization of this potential is inherently contingent upon a holistic strategy that simultaneously navigates significant external constraints, such as international sanctions limiting access to technology and capital, and internal organizational hurdles, including gaps in digital infrastructure and workforce readiness. Therefore, the imperative for both industry leaders and researchers is to pivot towards context-driven, strategic implementation pathways. Future scholarly efforts should prioritize the co-creation of localized roadmaps through in-depth qualitative inquiry into sector-specific barriers, and the development of pragmatic decision-support models to prioritize technologies based on dynamic assessments of implementation risk, resource requirements, and strategic impact. Concurrently, for practitioners, the journey begins with strategic piloting of high-impact, lower-complexity applications to build internal competency and demonstrate value, while actively fostering partnerships with domestic innovation ecosystems to build resilient, home-grown capabilities. Ultimately, the path forward for the cement industry lies in marrying a clear vision of technological possibility with an agile, adaptive, and resource-conscious approach to adoption, transforming present-day constraints into catalysts for targeted innovation and sustainable competitive resilience.

Implementation Barriers and Future Research Directions:

The implementation challenges, such as high capital investment costs, data privacy and legal considerations, workforce training requirements, and the development of an appropriate business model, are all significant factors that this current research, focusing on what technologies exist rather than how they are implemented, did not fully encompass. Consequently, for future research, it is strongly recommended that studies investigate the specific implementation challenges of these technologies within the cement industry. Additionally, a Capability-Attractiveness Analysis should be conducted to prioritize these applications based on deployment feasibility and potential return on investment. This future work must also explicitly address associated risks, such as over-reliance on AI systems or system vulnerabilities, while quantifying sector-specific benefits, such as the 2–5 percent energy savings previously noted by Pepe et al. (2025).

Data Availability Statement

Data available on request from the authors.

Acknowledgements

The authors would like to thank all participants of the present study.

Ethical considerations

The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

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