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Applications of the Internet of Things in the Sustainable Cement Industry

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Abstract

The cement industry plays a crucial role in construction and infrastructure development, carrying significant economic implications. While demand in developed countries has declined due to environmental concerns, Iran remains self-sufficient and a leading exporter in the Middle East. The Fourth Industrial Revolution has introduced the Internet of Things (IoT) as a transformative technology, delivering economic, environmental, and social benefits. Although historically resistant to change, the cement industry has recently begun adopting

IoT technologies, demonstrating notable progress in recent years. This study aims to identify and prioritize IoT applications within the sustainable cement industry in Iran. The research began by identifying IoT applications through a review of leading industry practices and academic literature. A sustainability-based framework was developed to evaluate these applications across economic, environmental, and social dimensions. The Best-Worst Method (BWM) was used to weight sustainability indicators, and the VIKOR method was applied to assess the relative attractiveness of each application. Capability indicators were also evaluated. A capability–attractiveness matrix was constructed to score and prioritize the applications accordingly. The study identified 13 relevant IoT applications for the cement industry. A set of 17 attractiveness indicators (grouped into economic, social, and environmental dimensions) and eight capability indicators (based on IoT architecture layers) were used in the evaluation. The applications were assessed using a capability–attractiveness matrix, and "Gas Monitoring" and "Temperature Measurement and Monitoring" were found to have the highest priority, indicating strong feasibility and strategic value for sustainable implementation.

Keywords: Internet of Things (IoT), Capability-Attractiveness Analysis, Cement industry, sustainability

Introduction

Cement production has steadily increased in response to population growth, urbanization, and expanding infrastructure development. It remains an indispensable industrial product essential for economic growth (Chaudhury et al., 2023). Cement is primarily used as a binder in concrete, which is a fundamental material for all types of construction, including housing, roads, schools, hospitals, dams, and ports, with much of the total construction cost dependent on it (Guo et al., 2024; Hoddinott Peter, 2011). However, the cement industry is among the largest consumers of energy and faces increasing pressure due to the environmental impact of high cement production, which alone contributes approximately 8% of global CO_2 emissions (de Lorena Diniz Chaves et al., 2021; Ren et al., 2023). For instance, in Iran, the cement industry is the second most energy-intensive sector after steel, accounting for 15% of total energy consumption and 18% of total natural gas consumption in the industrial sector (N. Ansari & Seifi, 2013). The energy consumption of the cement industry, whose annual production capacity is about 30 million tons, is equivalent to approximately 25 million barrels of crude oil (Madlool et al., 2011).

Despite these concerns, economic growth begins with a rapid build-up of industrial and transport infrastructure, and concrete remains the most widely used material for this purpose. (Cancio Díaz et al., 2017). The fact that cement production plants emit poisonous gases, pollutants, and hazardous particulate matter daily represents a significant environmental issue (Gupta et al., 2012). Therefore, improvements in energy efficiency in this area can significantly reduce environmental pollution (Gupta et al., 2012; S. Zhang et al., 2021). In addition, the high consumption of solid, liquid, and gaseous fossil fuels in manufacturing facilities and power generation plants to meet the electricity needs of cement production has not only led to massive emissions of various pollutants but also increased production costs (Barbhuiya, Kanavaris, et al., 2024; Ozturk & Dincer, 2022). Furthermore, considering the number of irreversible accidents, occupational diseases, and environmental damage occurring annually in the cement industry, risk reduction and prevention, along with ensuring the health of employees and the environment, have become central concerns in this industry (Etim et al., 2021; Zeb et al., 2019).

Meanwhile, with the advent of the Fourth Industrial Revolution, Internet of Things (IoT) technology has created various applications as well as diverse economic, social, and environmental benefits for different industries (Javaid, Haleem, Pratap Singh, et al., 2022). The revolution of the internet over the past couple of decades has proven that new forms of technology can impact all facets of business. Many studies have highlighted the potential of the Internet of Things for entrepreneurship, citing it not only as a new advancement in information and communication technology but also as a significant opportunity for revenue generation (Jami Pour et al., 2024; Molling & Zanela Klein, 2022). The Internet of Things has had a substantial impact on several fields, such as construction, operations, and management, through specialized services and efficient functionalities, alongside advancing sustainable development goals (Jia et al., 2019). The cement industry is also not untouched by this technology, as it holds the potential to address various issues in this domain (Fantana et al., 2013; Malik et al., 2021).

On the other hand, the implementation of IoT technology has consistently faced numerous technical, commercial, and legal considerations. Therefore, it is essential for developing countries to simultaneously take into account sustainable development goals and the feasibility of IoT implementation to make informed decisions regarding the selection of IoT applications.

Accordingly, providing a decision-making framework that incorporates both sustainability criteria and implementation capability is necessary in developing countries (Del Río Castro et al., 2021; Mäkitie et al., 2023). This study aims to prioritize IoT applications in the cement industry, unlike previous approaches that focused solely on a single aspect (M. Ansari et al., 2017). The fundamental research questions in this study are as follows:

Q1: What is the main and comprehensive set of IoT applications in the cement industry?

Q2: What are the critical capability-attractiveness criteria that must be considered for the successful implementation of IoT in the cement industry?

Q3: What is the relative importance (weight) of each of these criteria?

Q4: What are the implementation priorities of these applications in the cement industry of Iran, as a developing country?

To address these questions, this study attempts to provide systematic answers through a structured approach. The article is structured as follows: First, IoT applications in the cement industry are identified based on a literature review and expert opinions. Then, attractiveness criteria for these applications are selected based on achieving sustainability in the cement industry, and capability criteria are determined based on implementation feasibility using the Content Validity Index (CVI) method. Subsequently, the importance of each criterion is evaluated. Next, a new framework is developed using the Best-Worst Method (BWM), the VIKOR technique, and the capability-attractiveness matrix. Finally, the paper concludes with a discussion and proposes directions for future research.

Literature Review

Cement Industry Development

Industrial facilities, in general, and every sector within them, require continuous improvement and renovation to maintain competitive ability and operational sustainability (Javaid, Haleem, Singh, et al., 2022). The cement industry is no exception, particularly because outdated equipment and obsolete technologies in cement production factories contribute to the degradation of product quality and increased production costs. These factors gradually weaken product competitiveness and eventually lead to interruptions in operations (Georgiades et al., 2023; S. Zhang et al., 2021). Furthermore, modernizing machinery and improving efficiency reduce production costs, enhance product quality, and subsequently pave the way for stronger domestic market presence and export growth (Mondejar et al., 2021). For this reason, many cement production companies undertake developmental and modernization projects aligned with their strategic goals (Barbhuiya, Kanavaris, et al., 2024).

Development in the cement industry refers to the implementation of innovations aimed at improving efficiency, promoting sustainability, and increasing the competitiveness of cement production processes (Supino et al., 2016). Such developments include the introduction of new technologies, the adoption of more environmentally friendly processes, or the expansion of existing facilities to meet rising demand (Shahzad et al., 2022). The cement manufacturing process involves several steps, and improvements in production lines have typically focused on optimizing efficiency, increasing capacity, and adopting leading-edge technologies (Barbhuiya, Bhusan Das, et al., 2024; Barbhuiya, Kanavaris, et al., 2024). The characteristics of production line development depend on the aims, challenges, and opportunities acknowledged by the organization or company undertaking the project (Korhonen et al., 2023; Upadhyay et al., 2023).

Critical areas of development for the cement industry include the use of substitute fuels and raw materials, such as waste materials from plastics, rubber, and coal ash, aimed at reducing dependence on fossil fuels and thus lowering operational costs (Aranda Usón et al., 2013). Further research focuses on carbon capture, utilization, and storage (CCUS) technologies, designed to isolate CO2 emissions arising from cement production for various uses or underground storage, preventing their release into the atmosphere (Dziejarski et al., 2023; Guo et al., 2024; S. Zhang et al., 2021). Another development is the adoption of vertical roller mills, which are gaining acceptance because they can reduce energy consumption while simultaneously increasing production capacity (Fatahi et al., 2022). New technologies, such as specialized integrated robots, online equipment, information platforms, cement process digital applications (SaaS), Artificial Intelligence (AI), the IoT, and Advanced Process Control (APC), are being implemented to improve traditional operational methods (Tong et al., 2023).

Sustainability in the Cement Industry

Sustainability is defined as maintaining or continuing a specific condition or process over a long period, aimed at reducing significant detrimental effects on the environment, society, or economy (Moldan et al., 2012). It also involves meeting the needs of the current generation without compromising the ability of future generations to meet their own needs (Erling Holden et al., 2013).

Sustainability in the cement industry can be understood as adopting Environmental Management Practices (EMP) to minimize the environmental impacts of cement production, including activities related to raw material sourcing, production processes, and product usage (Dasgupta & Das, 2021). It also involves enhancing energy efficiency, using alternative fuels and raw materials, and reducing the clinker factor in cement production (Abdul-Wahab et al., 2021). Furthermore, sustainability in the cement industry highlights the need for more professional and skilled workers alongside innovative binders and material concepts to ensure long-term environmental and social resilience (Schneider et al., 2011).

The theme of sustainability in the cement industry ensures that chosen methodologies are environmentally friendly and supportive of social and economic well-being (Barbhuiya, Kanavaris, et al., 2024; Nawaz et al., 2020). It encompasses minimizing operating costs, environmental impact, and social implications, while maintaining productivity and efficiency in production methods (Taoumi & Lahrech, 2023). To ensure the sustainability of a cement plant, impacts on the environment, society, and economy need to be thoroughly evaluated, promoting long-term viability and good business practices in the sector (Putra et al., 2020).

In other words, sustainability in the cement industry refers to designing, producing, delivering, and disposing of cement products with minimal harm to society and the environment throughout the product’s life cycle, while remaining economically feasible for producers, consumers, and society (Ighalo & Adeniyi, 2020; Marsh et al., 2022). This definition highlights the minimization of negative impacts on society and the environment, the creation of economic resilience, and is based on a holistic framework and key performance indicators necessary to assess sustainability in the cement industry. Therefore, it aligns with a broader conceptualization of sustainable production (Sangwan et al., 2019).

Internet of Things

The IoT can be described as a system of tangible or intangible entities, or “things,” integrated with sensors, software, and connectivity to enable communication with other devices or systems through the internet (Angelini et al., 2018; Baiyere et al., 2020). The IoT framework comprises a set of rules, protocols, and regulations that govern data processing and message exchange between IoT devices, the cloud, and end-users. This framework supports IoT applications while abstracting the complexities of the underlying infrastructure protocols (Kumar et al., 2023).

In recent years, the Internet of Things has become a focal point in academic research and is considered a critical component of the future evolved internet (Ibarra-Esquer et al., 2017). This technology envisions a network of uniquely identifiable entities using standard communication protocols. IoT enables inter-object communication, creating smart environments where sensing and actuation activities are seamlessly integrated into the background, offering enhanced functionality through access to vast knowledge bases (Borgia, 2014).

IoT represents a fundamental transformation of the current internet into an interconnected network of objects that autonomously collect information from their surroundings and interact with the physical world(Gubbi et al., 2013). It is designed to allow computers to sense information autonomously, without human intervention, using internet standards to provide various services, including information transmission, analysis, applications, and communications (Aceto et al., 2019). IoT applications span numerous domains, including personal and home use, enterprises, urban services, and mobile applications (Sánchez-Corcuera et al., 2019). These applications are categorized based on criteria such as network availability, coverage, scalability, heterogeneity, repeatability, user participation, and impact(Asghari et al., 2019).

IoT has the potential to impact sectors such as healthcare, utilities, transportation, smart homes, smart cities, industrial control, and automation, among others (Umair et al., 2021). It thus represents a paradigm connecting physical entities with the digital world, enabling countless applications and services. Key characteristics include the seamless integration of sensing and actuation functions, with applications ranging from personal and organizational to utility and mobile domains (Gubbi et al., 2013).

IoT applications in the cement industry

IoT applications include designing intelligent transportation systems, tracking vehicle locations, monitoring movements, predicting future locations, and managing road traffic(Guerrero-Ibáñez et al., 2018; Zantalis et al., 2019). Additionally, IoT is utilized in logistics, manufacturing, retail, and pharmaceuticals, significantly impacting new ICT and enterprise systems. IoT-enabled devices possess functionalities such as self-configuration, self-optimization, self-protection, and self-healing (Xu et al., 2014).

IoT extends the Internet and Web into the physical world by introducing distributed spatial devices with embedded identification, sensing, or actuation capabilities (Miorandi et al., 2012). The application domains of IoT vary widely, encompassing smart object connectivity via extended internet technologies, support of enabling technologies, and innovative applications and services that create new business opportunities and markets (Chioma, 2020).

Essential characteristics of IoT include the abilities of sensing, communication, and interaction of smart devices with other devices or users (Borgia, 2014). These characteristics integrate computation, communication, and identification into everyday objects, enabling interaction with the immediate environment and forming ad hoc networks of connected devices (Stankovic et al., 2003). Security remains one of the most critical factors for the widespread adoption of IoT technologies and applications (Miorandi et al., 2012). Furthermore, IoT applications encompass public services, assisted living, e-health, and advanced learning (Memon et al., 2014). The features of IoT emphasize the need for fully interoperable connected devices and enhanced intelligence, enabling autonomous behavior while ensuring trust, privacy, and security (Jaime et al., 2023).

Applications of IoT in the Sustainable Cement Industry

After reviewing the preliminary list and conducting a focus group discussion, the final list of indicators related to the attractiveness and capability of IoT technology applications in the country’s cement industry was established. The finalized list of IoT applications relevant to the cement industry, as confirmed by the focus group, is presented in Table 1.

Table 1. Applications of IoT in the cement industry

Applications (Decision Options)	Authors (Year)
1. Preventive maintenance of equipment	Yao (2022)
2. Monitoring and controlling inhalable dust	Ciobanu et al. (2021); Nkhama et al. (2022)
3. Tracking materials (raw materials/final products)	Charan et al. (2020); A. Sharma & Khanna (2020)
4. Utilization of renewable energies	Gebreslassie et al. (2023); Monteiro et al. (2020); Putra et al. (2020)
5. Monitoring and controlling water quality and wastewater	Ipeaiyeda & Obaje (2017); Zhu et al. (2022)
6. Monitoring and controlling fossil fuel consumption	A. Rahman et al. (2015)
7. Monitoring gases (e.g., greenhouse gases and NOX)	Chaudhury et al. (2023)
8. Measuring and monitoring temperature	Bojja et al. (2021)

9. Measuring noise pollution levels	Khavanin et al. (2022); Thai et al. (2021)
10. Process flow control	Charan et al. (2020); Nagadasari & Bojja (2022); Yao (2022)
11. Product quality control	Charan et al. (2020); McNeil (2017); Yao (2022)
12. Remote control of facilities	Bojja et al. (2021); Charan et al. (2020); Nagadasari & Bojja (2022); Yao (2022)
13. Measuring and monitoring moisture levels (environmental and material moisture)	Charan et al. (2020)

According to these indicators, the final set of sustainability indicators across three dimensions, economic, social, and environmental, was compiled to assess the attractiveness of IoT technology in the cement industry. The Content Validity Index (CVI) was used to evaluate the extracted criteria. Experts rated the relevance of each criterion on a four-point scale (1-Irrelevant, 2-Needs major revision, 3-Relevant but needs minor revision, 4-Highly relevant). The CVI was calculated by dividing the number of experts who selected options 3 or 4 by the total number of experts. CVI values below 0.7 were rejected, values between 0.7 and 0.79 required revision, and values above 0.79 indicated criterion validity. The final list of sustainability indicators is presented in Table 2.

Table 2. Sustainability Sub-Indicators for Assessing the Attractiveness of IoT Technology in the Cement Industry

Main Dimension	Sustainability Sub-Indicator	Authors (Year)	CVI	Acceptable/ Rejected
EC. Economic	EC1. Cost savings in production	Ahmed et al. (2023); Pareek & Sankhla (2020); Walther (2018)	0.93	Acceptable
	EC2. Material consumption savings	Monteiro et al. (2020); Putra et al. (2020)	0.93	Acceptable
	EC3. Fossil energy consumption savings	Gebreslassie et al. (2023); Monteiro et al. (2020); Putra et al. (2020)	1	Acceptable
	EC4. Time savings in production processes	Bojja et al. (2021); Charan et al. (2020); Nagadasari & Bojja (2022); Walther (2018)	0.8	Acceptable
	EC5. execution accuracy improvement	Dasgupta & Das (2021); Pareek & Sankhla (2020)	0.93	Acceptable
	EC6. return on investment (ROI)	Imbabi et al. (2012); Sangwan et al. (2019)	1	Acceptable
	EC7. Flexibility and optionality	Yu et al. (2021)	0.53	Rejected
SO. Social	SO1. Attention to local community welfare	Sangwan et al. (2019); Schneider et al. (2011)	0.93	Acceptable
	SO2. client satisfaction	Chand & Tarei (2024)	0.8	Acceptable
	SO3. Worker health and safety	Dasgupta & Das (2021); Putra et al. (2020)	0.86	Acceptable
	SO4. Training and knowledge development	Schneider et al. (2011)	0.93	Acceptable
	SO5. Product and service labelling	Siraj et al. (2022)	0.8	Acceptable
EN. Environmental	EN1. Waste reduction	Gebreslassie et al. (2023); Sangwan et al. (2019)	1	Acceptable
	EN2. Soil pollution control	Ciobanu et al. (2021); El-Sherbiny et al. (2019); Pareek & Sankhla (2020)	1	Acceptable
	EN3. Noise pollution control	Marques & Pitarma (2020)	0.8	Acceptable

	EN4. Control of harmful gas emissions	Ciobanu et al. (2021); Hargis et al. (2021); Monteiro et al. (2020); Pareek & Sankhla (2020); Sangwan et al. (2019)	1	Acceptable
	EN5. Water pollution monitoring	Jena et al. (2020); Zhu et al. (2022)	1	Acceptable
	EN6. Energy consumption control and savings	Dasgupta & Das (2021); Gebreslassie et al. (2023); Pareek & Sankhla (2020)	0.93	Acceptable
	EN7. Control and monitoring of inhalable dust	Ciobanu et al. (2021)	0.93	Acceptable
	EN8. Recycling and reuse	Keßler et al. (2021)	0.66	Rejected
	EN9. Local procurement	Hafsa et al. (2021)	0.66	Rejected

The final list of IoT capability indicators in the cement industry, based on the focus group's opinion and the Content Validity Index, is presented in Table 3.

Table 3. Indicators of IoT Implementation Capability in the Cement Industry

Criteria Name	Authors (Year)	CVI	Acceptable/ Rejected
CAP1. Access to Devices and Gateways	Beniwal & Singhrova (2022)	1	Acceptable
CAP2. Networking Capability (Wired and Wireless)	Hadi et al. (2018); Sood et al. (2016)	1	Acceptable
CAP3. Platform Creation Capability (Platforming)	Fahmideh & Zowghi (2020); L. L. Zhang (2015)	0.8	Acceptable
CAP4. Application Development Capability (App)	Baek et al. (2023); Patel & Cassou (2015)	0.93	Acceptable
CAP5. Security and Privacy Protection Capability	Chanal & Kakkasageri (2020)	0.8	Acceptable
CAP6. IoT Project Management Capability	Ghimire et al. (2017); Marnewick & Marnewick (2020)	0.86	Acceptable
CAP7. Compliance with Laws, Regulations, and Standards	Tzafestas (2018)	0.93	Acceptable
CAP8. Budgeting for Installation, Operation, and Maintenance	M. Rahman et al. (2019)	1	Acceptable
CAP9. Managerial capabilities	Vafaei-Zadeh et al. (2025)	0.66	Rejected

Research gaps

Multi-Criteria Decision-Making (MCDM) techniques have been developed to select the best option from a limited set of alternatives based on multiple criteria(Heidary Dahooie et al., 2023). Previous studies indicate that these techniques effectively handle conflicting criteria and facilitate consensus among multiple experts, making them valuable tools in technology management decision-making (Macharis & Bernardini, 2015). However, in the context of the sustainable cement industry, the application of MCDM approaches has so far received limited attention.

In this regard, several studies have explored the use of MCDM methods in the IoT domain, particularly for selecting appropriate IoT applications, assessing associated challenges, identifying implementation factors, and prioritizing industries for sustainable IoT adoption. Nevertheless, a critical review of the literature reveals that few studies have applied MCDM methods specifically for selecting IoT applications within the cement industry. To address this research gap, a summary of relevant studies is presented in Table 4.

Table 4. A summary of previous studies.

Research aims/ objectives	Country	MCDM Technique Used	Sustainability Dimensions Addressed	Organizational Capability Considered	Authors (Year)
Investigate the main barriers to implementing Industry 4.0 in the Brazilian cement industry	Brazil	Fuzzy AHP	✗	✓	Júnior et al. (2025)
Evaluation of Available Options for the Sustainable Transformation of Pakistan's Cement Industry	Pakistan	MAMCA	✓	✗	Ali et al. (2024)
Investigate key drivers influencing the adoption of Industry 4.0 technologies within a circular economy model focusing on an industrial ecosystem including the cement industry.	India	MICMAC, TISM	✗	✓	Vimal et al. (2022)
Proposes a model for evaluating the performance of Green Supply Chain Management (GSCM) application within the cement industry.	Turkey	Fuzzy DEMATEL	✓	✗	Kazancoglu et al. (2018)
A framework to prioritizing industries for developing sustainable IoT	Iran	AHP, TOPSIS, and ELECTRE	✓	✗	Zarei et al. (2016)

As shown in Table 4, many of these studies have relied on techniques such as the Analytic Hierarchy Process (AHP), which often leads to high inconsistency ratios and unstable results due to the large number of pairwise comparisons required. In contrast, the BWM requires fewer comparisons, allows calculation of consistency ratios, and is generally more intuitive for expert respondents. In this study, the BWM was employed to determine the weights of the decision criteria. This method, by addressing key limitations of AHP, is increasingly recognized as one of the most effective and reliable MCDM techniques.

Furthermore, making decisions based on both sustainability and implementation capability dimensions simultaneously requires a structured matrix to guide decision-makers. To provide structured guidance for such decision-making, this study employs the capability-attractiveness matrix. Unlike previous research, which typically focused on only one of these dimensions, the present study integrates both. In this framework, the "attractiveness" dimension evaluates each IoT application based on its alignment with sustainable development goals, while the "capability" dimension assesses the practical feasibility of implementation. Ultimately, the position of each IoT application within the matrix facilitates comprehensive strategic prioritization.

Methodology

This study is applied-quantitative research conducted using a descriptive survey method. To ensure the reliability and validity of expert assessments, a snowball sampling technique was employed to select the experts. This approach is designed to reduce selection bias by combining initial expert recommendations and expanding the network to include experts from diverse positions and geographical locations. The final panel comprises 12 experts with relevant experience in the cement industry and IoT implementation. Their qualifications, professional roles, and years of experience are summarized in Table 5.

Table 5. Experts' profiles

No.	Position	Area of Expertise	Work Experience (Years)	Affiliation (City)
1	Secretary of the National Cement Employers' Association	Cement Industry	30+	Tehran
2	Senior Manager, Cement Employers' Association	Cement Industry	30+	Tehran
3	CEO of a Nahavand cement company	Cement Industry	30+	Tehran
4	Professor, Faculty of Management, University of Tehran	Industry	30+	Tehran
5	Senior Specialist, X-RAY and Physics Unit	Cement Industry	20	Hamedan
6	Head of IT and Informatics, Hegmatan Cement	Cement Industry	15	Hamedan
7	Supervisor, Standards and ISO Unit, Hegmatan Cement	Cement Industry	12	Hamedan
8	Board Member, IoT Implementation Company	IoT Implementation	10	Tehran
9	Board Member, IoT Implementation Company	IoT Implementation	8	Tehran
10	Senior Specialist, X-RAY Unit, Hegmatan Cement	Cement Industry	8	Hamedan
11	Board Member, IoT Implementation Company	IoT Implementation	6	Tehran
12	Supervisor, Material Adjustment Unit, Hegmatan Cement	Cement Industry	6	Hamedan

The following diagram illustrates the execution process of this study.

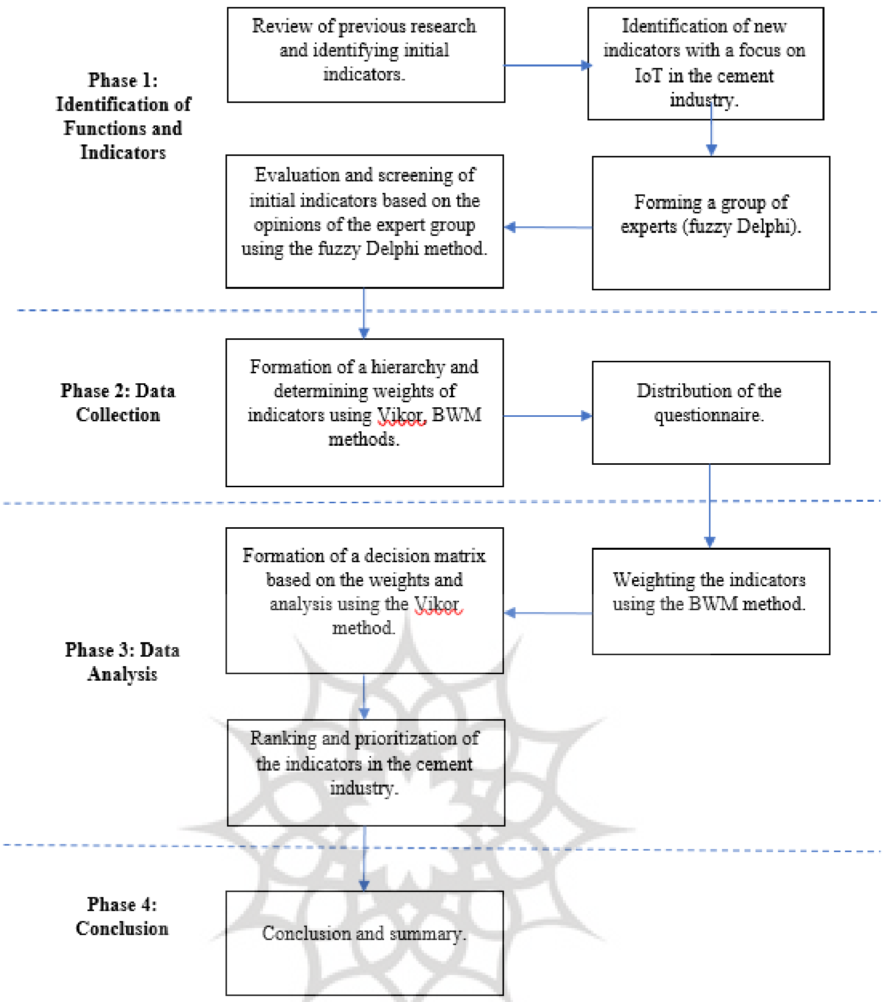

Figure 1. Research steps

In this research, data were collected through two primary methods: documentation and questionnaires. Initially, library studies and a review of the research literature were conducted to examine the theoretical foundations and essential concepts of the subject. Following this, relevant experts were interviewed to extract the required indicators and analyze various dimensions of the research. Subsequently, questionnaires developed using Excel were administered to assess and measure these indicators. This mixed-method approach, combining insights from library research and experts' practical experience, enables a more comprehensive and in-depth analysis of the subject. Additionally, by employing both interviews and questionnaires, the study facilitated direct interaction with experts, allowing for both quantitative and qualitative measurements of the indicators. This methodology enhances the accuracy and completeness of the research findings and promotes active engagement with experts while collecting data from diverse sources, thus contributing to the quality and credibility of the results.

For data analysis, multi-criteria decision-making methods such as the VIKOR method were employed to evaluate the attractiveness and capability of each application. The BWM was used to weight the indicators by determining the importance of each and calculating the final scores accordingly. The VIKOR method is particularly valuable due to its ability to handle uncertainties and incomplete information, facilitating decision-making in situations where accurate and complete data are unavailable. Moreover, the use of BWM for weighting ensures a hierarchical and precise decision-making process. In the subsequent step, applications were prioritized using an attractiveness-capability matrix that integrates information on these two aspects for each application. This matrix enables evaluation within a unified framework by combining attractiveness and capability data, thereby identifying their relative importance. By employing these diverse decision-making methods, the research provides a precise and comprehensive assessment of each application's attractiveness and capability, ensuring the validity of the results obtained from data analysis.

Best-Worst Method

The BWM is one of the latest techniques for evaluating the weights of indicators and options, belonging to the category of pairwise comparison methods (Rezaei, 2015). This method can be applied to both indicators and options, determining their values based on the indicators. For simplicity, the explanation focuses on options, although the same process applies to determining the weights of indicators (Liu et al., 2021).

BWM divides pairwise comparisons between indicators (or options) into two types: reference (or main) and secondary (or sub) comparisons (Shang et al., 2022; H. Sharma et al., 2022). Typically, experts identify one option as the best and another as the worst, then compare the remaining options with these two. When an option is compared with the best or worst option, a reference or main comparison is made; when neither options being compared is considered the best or worst, a secondary or sub-comparison takes place (Rezaei, 2015). The BWM technique requires only reference comparisons, eliminating the need for experts to perform secondary comparisons. Consequently, fewer pairwise comparisons are necessary, which not only enhances accuracy but also improves the efficiency of the decision-making process .

VIKOR

The VIKOR method was introduced by Opricovic in 1998 and further developed by Opricovic and Tzeng in 2002. The VIKOR algorithm is a multi-criteria decision-making (MCDM) method used for ranking options in decision-making problems involving multiple criteria to select the best alternative (Cristóbal, 2011; Liao & Xu, 2013). In this algorithm, exact numerical values are used to represent information related to criteria and options. Its key features include modeling uncertainty and ambiguity related to criteria, as well as representing weights and scores using precise numbers.

The method aims to rank alternatives based on a set of criteria. It is a consensus-driven MCDM approach where the ranking criterion is based on the degree of proximity to the optimal solution. VIKOR seeks to maximize group satisfaction while minimizing the impact of individual opposition (Opricovic, 2011).

Attractiveness-Capabilities Analysis

Establishing a link between strategies and technologies is an emerging approach in industrial and technology management. The attractiveness-competence matrix, also known as technology portfolio analysis, is a model developed by the Stanford Research Institute to assess this relationship (Mokhtarzadeh et al., 2018). The attractiveness-competence matrix serves as a valuable tool for identifying technological priorities and devising appropriate strategies. When allocating resources such as capital, human resources, equipment, and physical facilities to strategic plans, internal competition often arises to overcome resource constraints (Sirmon et al., 2008). Indeed, the results of the attractiveness-capability evaluation determine the strategic position of technologies and identify key technologies (Mohaghegh & Shirazi, 2017). However, effective use of this tool requires defining and developing factors and criteria that enable multidimensional and comprehensive evaluation (Jolly, 2012).

Various analyses based on the attractiveness model can be conducted, as illustrated in the diagram. Regarding each IoT function in the cement industry, a strategic approach can be adopted for applications in the following four areas:

Area 1 - Transformational technologies in this area have high attractiveness but low industry competence. These technologies are non-essential; the appropriate strategy is either to outsource them or not prioritize them.

Area 2 - Technologies here have high attractiveness but low industry or company competence. The appropriate strategy is to seek partnerships with successful companies or enhance internal capabilities.

Area 3 - Technologies in this area have low attractiveness but high industry competence. Given the industry’s dominance over these technologies, the strategy could be to transfer them to other sectors for use or replace them with other technologies.

Area 4 - Technologies in this area are highly important, possessing both high attractiveness and high industry competence. The appropriate strategy is to maintain their position, conduct internal research and development to enhance them, and prioritize their applications to fully harness their potential.

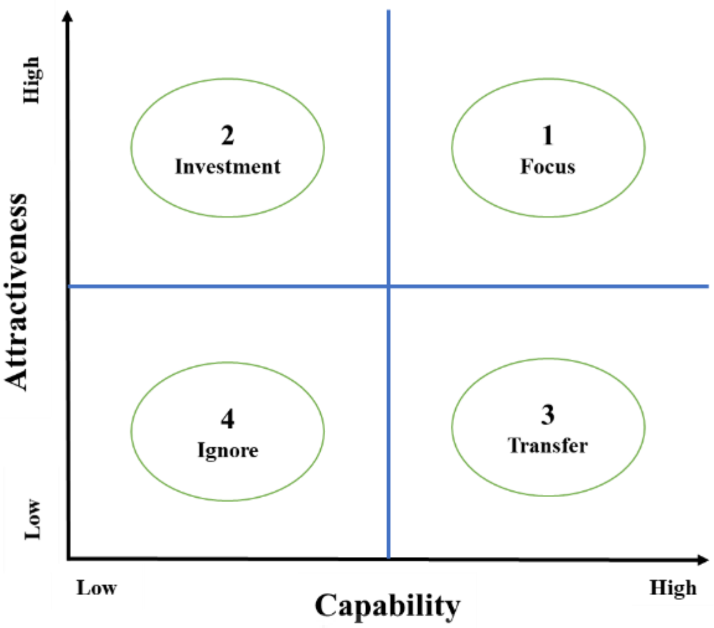

Figure 2. Attractiveness-Capability Matrix (Ghazinoory et al., 2009)

To account for the values of attractiveness and competence for each application, the following approach is used (Nasrollahi et al., 2022):

Step 1: Calculate the weight of each indicator and subcategory using the BWM.

Step 2: Calculate and record the score and rank of each application using the VIKOR method. In both steps, expert opinions are collected through questionnaires.

Step 3: Determine the cutoff point by considering the Q value from the VIKOR method. The average Q value of the attractiveness sub-indicators and competence indicators forms the cutoff point.

Step 4: Display and plot the resulting score for each application on the graph according to the cutoff point.

Results and Discussion

The result of the Best-Worst method

In this step, using the BWM method, the best and worst indicators were determined by six experts in the designed questionnaire for this section. The selected indicators and sub-indicators are listed below based on their selection by the experts. After recording and registering the expert opinions, the weights of the attractiveness and competence indicators and sub-indicators were summarized using the arithmetic mean method.

Then, in the next step, the aggregated weights of the economic, social, and environmental sub-indicators were multiplied by the weights derived from sustainability to determine the final weight of these sub-categories according to their importance in the sustainability topic.

The results are presented in Tables 6, 7, and 8.

Table 6. Weights of Sustainability Indicators (Attractiveness)

Indicator	Experts' Weights (1-6)	Aggregated Weight
EC	0.752, 0.769, 0.708, 0.750, 0.705, 0.663	0.725
SO	0.181, 0.154, 0.208, 0.150, 0.218, 0.275	0.198
EN	0.667, 0.077, 0.083, 0.100, 0.077, 0.063	0.078

Table 7. Weights of Sustainability Sub-indicators (Attractiveness)

Indicator	Experts' Weights (1-6)	Local Weight	Global Weight
EC1	0.379, 0.521, 0.41, 0.335, 0.412, 0.483	0.423	0.307
EC2	0.148, 0.116, 0.123, 0.152, 0.105, 0.152	0.132	0.096
EC3	0.111, 0.099, 0.098, 0.152, 0.105, 0.087	0.108	0.078
EC4	0.089, 0.087, 0.082, 0.091, 0.075, 0.087	0.085	0.062
EC5	0.221, 0.139, 0.246, 0.227, 0.261, 0.152	0.208	0.151
EC6	0.053, 0.039, 0.041, 0.043, 0.043, 0.04	0.043	0.032
SO1	0.259, 0.17, 0.194, 0.167, 0.191, 0.138	0.186	0.037
SO2	0.466, 0.657, 0.619, 0.633, 0.551, 0.662	0.598	0.118
SO3	0.172, 0.121, 0.129, 0.139, 0.191, 0.138	0.149	0.03
SO4	0.103, 0.052, 0.058, 0.061, 0.067, 0.062	0.067	0.013
EN1	0.145, 0.09, 0.182, 0.143, 0.156, 0.14	0.143	0.011
EN2	0.108, 0.108, 0.091, 0.072, 0.117, 0.14	0.106	0.008
EN3	0.087, 0.077, 0.078, 0.086, 0.117, 0.084	0.088	0.007
EN4	0.337, 0.425, 0.41, 0.369, 0.353, 0.303	0.366	0.029
EN5	0.034, 0.052, 0.034, 0.044, 0.034, 0.037	0.039	0.003
EN6	0.072, 0.068, 0.068, 0.072, 0.067, 0.084	0.072	0.006
EN7	0.217, 0.18, 0.137, 0.215, 0.156, 0.211	0.186	0.015

Table 8. Weights of Competence Indicators

Indicator	Experts' Weights (1-6)	Local Weight
CAP1	0.332, 0.310, 0.319, 0.319, 0.358, 0.417	0.343
CAP2	0.057, 0.069, 0.047, 0.058, 0.055, 0.064	0.058
CAP3	0.199, 0.172, 0.141, 0.205, 0.218, 0.103	0.173
CAP4	0.100, 0.086, 0.085, 0.102, 0.109, 0.103	0.097
CAP5	0.133, 0.172, 0.212, 0.136, 0.087, 0.103	0.141
CAP6	0.080, 0.086, 0.106, 0.082, 0.087, 0.086	0.088
CAP7	0.066, 0.069, 0.060, 0.068, 0.055, 0.086	0.067
CAP8	0.033, 0.034, 0.031, 0.029, 0.031, 0.040	0.033

The consistency ratio is calculated based on the formula by substituting the consistency values and ξ^*:

$$Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index} \tag{1}$$

Table 9. Consistency Index Values for "Attractiveness Sub-Indicators"

Sustainability' Dimensions	Experts					
	1	2	3	4	5	6
EC	0.063	0.172	0.083	0.119	0.111	0.126
SO	0.052	0.192	0.155	0.202	0.213	0.169
EN	0.097	0.116	0.137	0.061	0.115	0.118

Table 10. Consistency Index Values for "Capability Indicators"

Experts	1	2	3	4	5	6
CR	0.066	0.036	0.104	0.09	0.087	0.097

It can be concluded that, based on the results presented in the tables above and the calculated consistency rates (all less than 1) for the attractiveness sub-indicators and capability indicators, the pairwise comparisons have been correctly conducted. These values indicate proper consistency and reliability of the questionnaire.

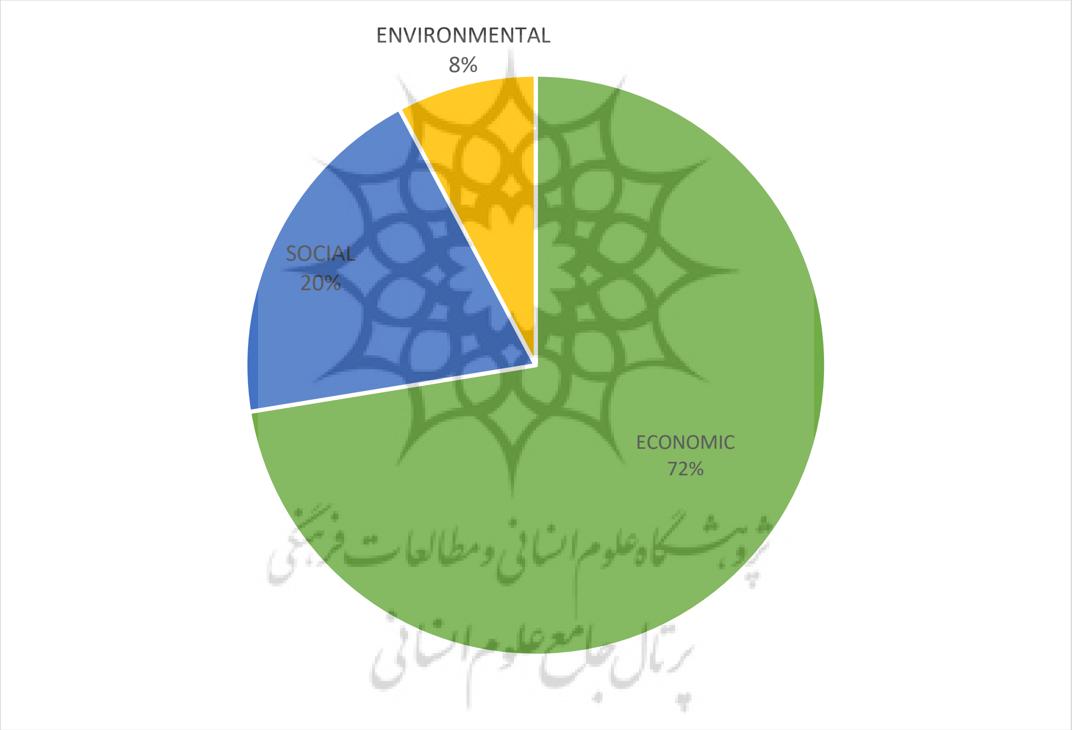

Figure 3. Weight of Sustainability Indicators (Attractiveness)

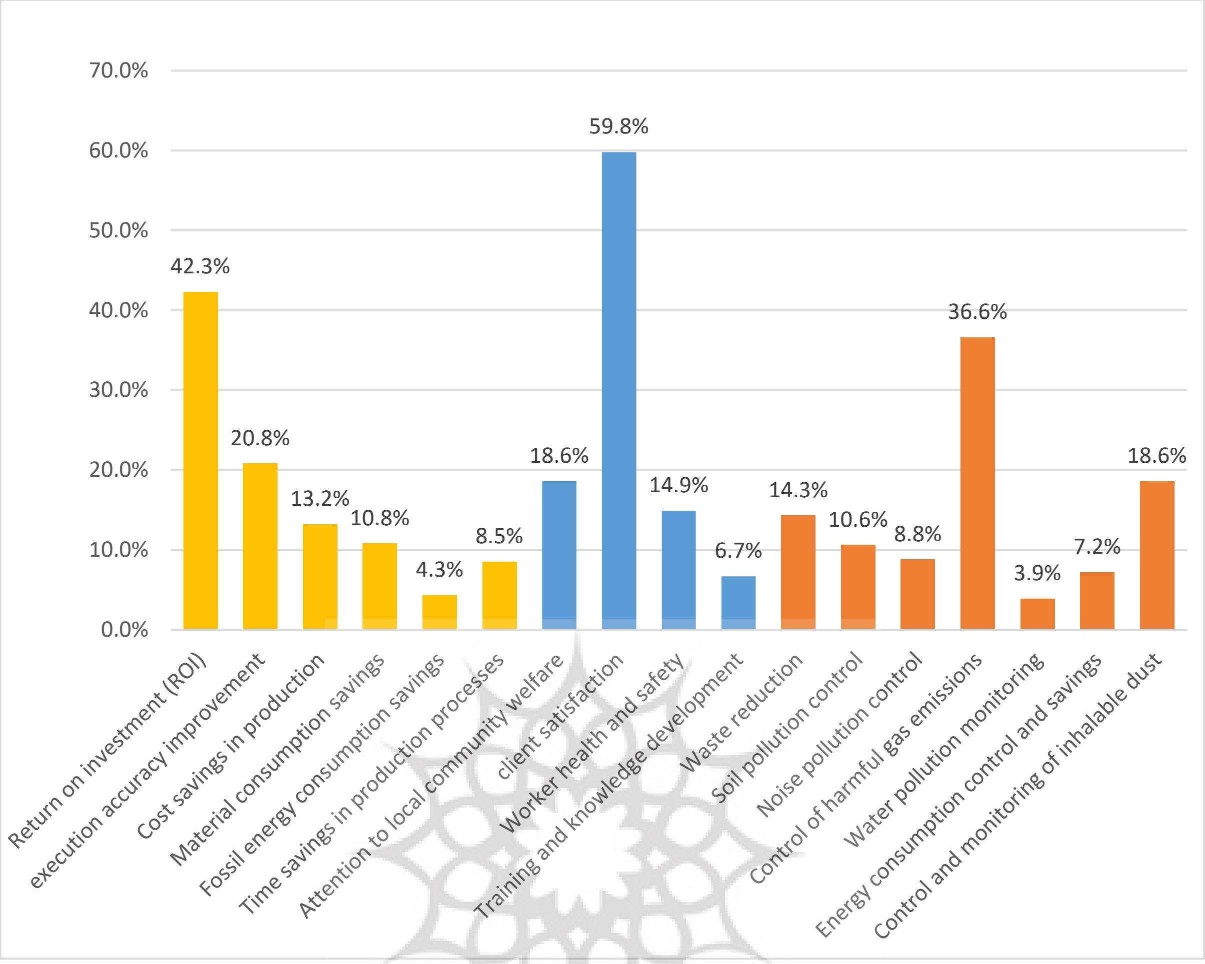

Figure 4. Comparison of Total Weight of Sustainability Indicators (Attractiveness)

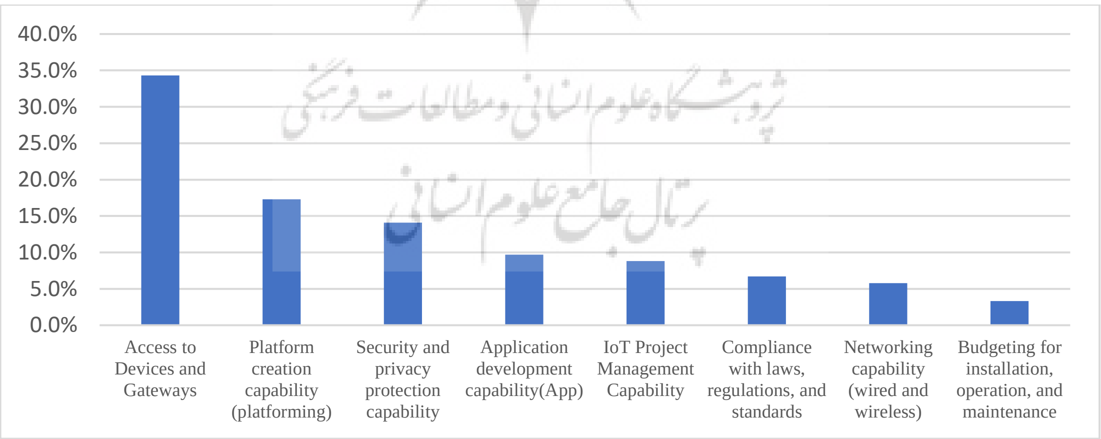

Figure 5. Weight of Capability Indicators

The findings from the Best-Worst Method indicated that among the sustainability dimensions, the environmental dimension had the highest importance at 72%, while the economic dimension had the lowest at 8%. Within economic attractiveness indicators, "return on investment," at 42.3%, was identified as the most significant, whereas "fossil fuel energy savings," at 4.3%, was the least significant. Among social indicators, "client satisfaction," at

59.8%, was deemed most significant, whereas "training and knowledge development," at 6.7%, was the least significant. For environmental indicators, "controlling harmful gas emissions," at 36.6%, was the most significant, while "water pollution monitoring," at 3.9%, was the least significant. Regarding capability indicators, "access to tools and portals," at 34.3%, was the most significant, whereas "budget provision," at 3.3%, was the least significant. Finally, the ranking of IoT applications in the cement industry was performed using the VIKOR method.

The result of VIKOR

Forming the Decision Matrix

In this method, the decision matrix was first created using the evaluations provided by six experts regarding the scores for each attractiveness sub-indicator and capability indicator for IoT applications in cement industry projects. The responses were aggregated using the geometric mean. Since most indicators were benefit-based, the highest values were considered ideal, and the lowest were anti-ideal, except for two cost-based indicators, for which the reverse applied. After normalizing the decision matrix, the values of S^* and R^* were determined, followed by the calculation of R and S. The results are presented in Table 11.

Table 11. Attractiveness and Capability Index: S_i and R_i Values

Application	Attractiveness Index				Capability Index			
	S_i Value	Rank	R_i Value	Rank	S_i Value	Rank	R_i Value	Rank
1. Preventive maintenance of equipment	1.492	4	0.286	8	1.216	12	0.3	9
2. Monitoring and controlling inhalable dust	0.998	2	0.229	2	0.81	7	0.3	9
3. Tracking materials (raw materials/final products)	1.649	7	0.28	6	0.986	8	0.3	9
4. Utilization of renewable energy	3.016	12	0.3	9	1.002	9	0.225	7
5. Monitoring and controlling water quality and wastewater	3.245	13	0.3	9	0.445	5	0.127	4
6. Monitoring and controlling fossil fuel consumption	2.172	11	0.3	9	0.372	4	0.133	5
7. Monitoring gases (e.g., greenhouse gases and NOX)	0.62	1	0.182	1	0.449	6	0.133	5
8. Measuring and monitoring temperature	1.613	6	0.236	3	0.184	1	0.106	3
9. Measuring noise pollution levels	1.871	9	0.284	7	0.32	3	0.08	2
10. Process flow control	1.73	8	0.268	5	1.307	13	0.3	9
11. Product quality control	1.536	5	0.24	4	1.605	10	0.238	8
12. Remote control of facilities	1.317	3	0.3	9	1.169	11	0.3	9
13. Measuring and monitoring moisture levels (environmental and material moisture)	1.989	10	0.3	9	0.205	2	0.08	1

Calculation of the VIKOR Index (Q)

Since the value of Q (the output of the VIKOR method) is cost-related and ranges between zero and one, this study considers (1 - Q) as the capability-attractiveness score and the basis for evaluation. In this step, a normalized value of V=0.5 was used. Based on the VIKOR method formulas, the calculated values of S^*f were 0.620 for the attractiveness sub-indicators and 0.184 for the capability indicators. The calculated values of R^*were 0.182 for the attractiveness sub-indicators and 0.080 for the capability indicators. The results of the Q factor calculations, without normalization, are presented in Table 12.

Table 12. Q Score of IoT Applications in Attractiveness and Capability Indicators

Applications	Capability Indicators		Attractiveness Indicators	
	Q Score	Rank	Q Score	Rank
1. Preventive maintenance of equipment	0.04	12	0.394	6
2. Monitoring and controlling inhalable dust	0.221	9	0.73	2
3. Tracking materials (raw materials/final products)	0.143	10	0.389	7
4. Utilization of renewable energy	0.306	7	0.044	12
5. Monitoring and controlling water quality and wastewater	0.777	5	0	13
6. Monitoring and controlling fossil fuel consumption	0.795	4	0.204	11
7. Monitoring gases (e.g., greenhouse gases and NOX)	0.761	6	1	1
8. Measuring and monitoring temperature	0.941	2	0.583	3
9. Measuring noise pollution levels	0.94	3	0.33	9
10. Process flow control	0	13	0.426	5
11. Product quality control	0.248	8	0.58	4
12. Remote control of facilities	0.061	11	0.367	8
13. Measuring and monitoring moisture levels (environmental and material moisture)	0.991	1	0.239	10

Determining the Cut-off Point

To determine the cut-off point, we first calculated the average of the 1-Q capability scores from Table 4-20, obtaining a value of 0.479. This value represents the cut-off point on the capability axis (vertical axis) of the chart. Next, we calculated the average of the 1-Q attractiveness scores from Table 4-21, obtaining a value of 0.407. This represents the cut-off point on the attractiveness axis (horizontal axis) of the chart. Based on the values obtained in the previous step and the determined cut-off points, the position of each IoT application in the cement industry on the attractiveness-capability matrix was identified, as shown in Table 13.

Table 13. Attractiveness and Capability Scores for IoT Applications in Sustainable Cement Industry

IoT Applications in Sustainable Cement Industry	Capability Score	Attractiveness Score	Zone
Monitoring gases (e.g., greenhouse gases and NOX)	0.761	1	4
Monitoring and controlling inhalable dust	0.221	0.73	2
Measuring and monitoring temperature	0.941	0.583	4
Product quality control	0.248	0.58	2
Process flow control	0	0.426	2
Preventive maintenance of equipment	0.04	0.394	1
Tracking materials (raw materials/final products)	0.143	0.389	1
Remote control of facilities	0.061	0.367	1
Measuring noise pollution levels	0.94	0.33	3
Measuring and monitoring moisture levels (environmental and material moisture)	0.991	0.239	3
Monitoring and controlling fossil fuel consumption	0.795	0.204	3
Utilization of renewable energy	0.306	0.044	1
Monitoring and controlling water quality and wastewater	0.777	0	3

Then, the corresponding points were marked on Figure 6 (the Capability-Attractiveness Matrix), and the final chart was obtained.

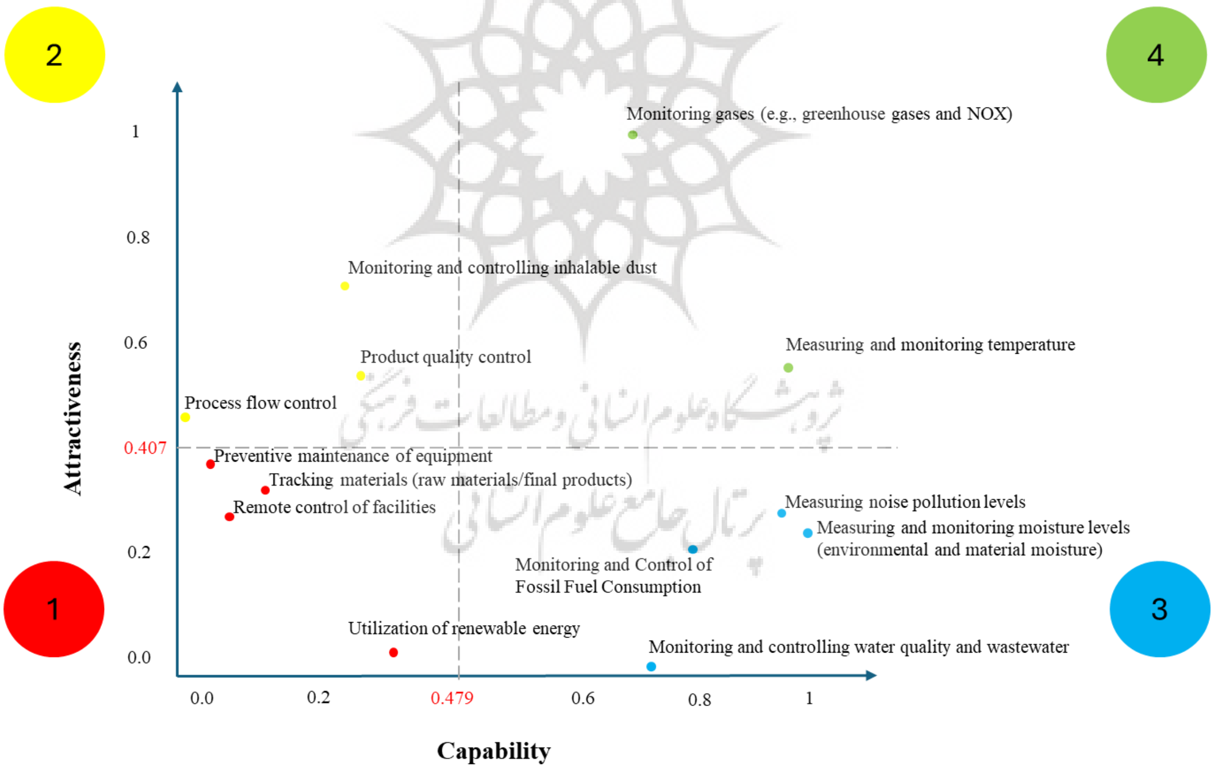

Figure 6. The Capability-Attractiveness Matrix

This study aimed to develop a framework for evaluating IoT applications in the cement industry. Figures 4 and 5 indicate a comparison of the weights assigned to the two criteria of sustainable development and implementation capability.

Based on the sustainable development goals, the economic dimension received the highest weight, which is consistent with the results of a previous study. It may be because economic factors, such as cost efficiency and return on investment, directly influence the feasibility and adoption of new technologies in capital-intensive industries such as cement production (Jaspers & Proff, 2025). Moreover, emphasizing economic metrics can encourage managers to pursue digital transformation initiatives, resulting in positive social and environmental impacts (Alojail & Khan, 2023).

Among the economic criteria, return on investment (ROI) is the most important. It could be due to its direct effect on decision-making regarding technology adoption and resource allocation. In developing countries, ROI plays a key role, as financial limitations require prioritizing projects with clear and timely benefits to minimize the risks of adopting new technologies (Atieh et al., 2023).

In the social dimension, client satisfaction was recognized as the most important criterion. This prioritization is primarily attributed to the cement industry's close relationship with its end-users and stakeholders, where customer trust and satisfaction directly influence market competitiveness and long-term business sustainability (Love et al., 2025). Regarding the environmental dimension, the control of harmful gas emissions is more important than other factors. Data supporting this reveal that the cement industry is a major contributor to toxic emissions, including greenhouse gases such as CO_2 and NO_x, which pose serious risks to environmental and public health globally (Elehinafe et al., 2022).

In terms of implementation capability, access to devices and gateways was evaluated as the most critical factor. This is because a reliable and extensive network of interconnected devices forms the backbone of any IoT system, ensuring seamless data collection and communication. Without sufficient access to these hardware components, the deployment and scalability of IoT applications are significantly constrained. Establishing this foundational infrastructure is essential before advancing to more complex applications, thus giving it precedence over other capability criteria (Bello et al., 2017).

Accordingly, the applications "Gas Monitoring (e.g., greenhouse gases and NOx)" and "Temperature Measurement and Monitoring" were positioned in the fourth quadrant of the capability-attractiveness matrix, reflecting both high attractiveness and high implementation capability. This placement highlights their immediate priority for deployment due to their considerable environmental relevance and technological readiness.

Applications such as "Noise Pollution Measurement," "Humidity Measurement and Monitoring," "Monitoring and Control of Fossil Fuel Consumption," and "Water and Wastewater Quality Monitoring and Control" were placed in the third quadrant due to their high implementation capability but relatively lower attractiveness. These solutions are technically viable but currently offer less evident sustainability impact, suggesting their potential for future prioritization.

Meanwhile, applications like "Monitoring and Control of Inhalable Dust," "Product Quality Control," and "Process Flow Control" fell into the second quadrant, characterized by high attractiveness but lower implementation capability. This indicates that despite their importance in advancing sustainability goals, infrastructural and operational challenges must first be addressed to support their effective adoption.

Finally, applications including "Material Tracking," "Remote Control of Installations," "Preventive Equipment Maintenance," and "Utilization of Renewable Energy" were located in the first quadrant, denoting low attractiveness and low capability. Although these are presently less feasible and impactful, they may become strategic long-term objectives as technological and economic conditions evolve.

Conclusion

One of the most significant challenges in recent years for developing countries such as Iran has been addressing production sector issues to achieve sustainable development goals through innovative technological solutions like the IoT. On the other hand, the cement industry is considered one of the most unsustainable sectors worldwide due to its substantial environmental, social, and economic problems. Consequently, this industry has attracted considerable attention from researchers in recent years. Therefore, the identification and prioritization of IoT applications based on sustainability criteria and implementation capability in Iran, as a case study, have been conducted. Iran, as one of the largest producers and exporters of cement globally, plays a crucial role in the economy of this industry.

The major findings of the research include:

1. This research first identified the main IoT applications in the cement industry based on a literature review and experts’ opinions.
2. This study distinguished a list of the most important attractiveness criteria for sustainability in the cement industry, as well as capability criteria for IoT implementation.
3. This study assessed the relative importance of identified criteria in the cement industry of Iran.
4. An Attractiveness-Capability Matrix was proposed to identify areas for future investment by considering the two criteria of sustainability and IoT implementation capability.
5. By focusing on the case of Iran as a developing country, our research provides insights into the applicability of the proposed framework in resource-constrained environments.

This is particularly valuable because decision-making frameworks designed for developed countries may not be fully suitable or directly applicable in developing contexts.

The findings of this study for Iran, as a developing country, indicate that from the sustainability perspective, the economic criterion, and from the capability perspective, the Platform Creation Capability was recognized as the most significant weight. The results show that "Gas Monitoring (e.g., greenhouse gases and NOX)" and "Temperature Measurement and Monitoring" are prioritized as the top IoT applications, evaluated using the attractiveness-capability matrix. These findings not only contribute to the existing literature but are also valuable for managers and policymakers in both public and private sectors.

Furthermore, certain limitations of this study should also be taken into consideration. For example, the given priorities are more appropriate for Iran due to the significant differences in the economic, technological, and infrastructural conditions of the cement industry compared to developed countries. However, to increase the generalizability of the results, it is necessary to consider the application of the proposed framework in other countries. Previous research has shown that in developed countries such as China and some European countries, IoT applications are more aimed at improving energy efficiency and precise control of pollutants, and advanced information technology infrastructures provide faster adoption for these technologies (Ahmed et al., 2023; Khurshid et al., 2023). In contrast, in developing countries, including Iran, challenges such as infrastructure limitations, high costs, and weak technical knowledge have prevented the widespread deployment of IoT in the cement industry (Ugural et al., 2024), but studies such as Hegab et al. (2023) show that by applying adaptive strategies and proper prioritization, significant benefits in sustainability and productivity can be achieved.

Consequently, generalizing the results to other countries should be approached with caution, and independent studies should be conducted considering the economic, technological, and logistical conditions of those countries. Future research can adjust and optimize the indicators and their weights according to the specific contexts of different countries to ensure broader applicability.

Moreover, the framework for weighting the attractiveness and feasibility criteria in this study is adaptable and adjustable to different economic and technological conditions in other countries. This could allow the model to be used in different countries by changing the weights of the criteria and indicators to match the local challenges and opportunities of each country. It is also suggested that future research should test and optimize this model in different countries by examining local and infrastructural characteristics in more detail.

Finally, since this study aligns with expert opinions, it is essential to conduct experimental research to assess the effectiveness of the proposed IoT applications. Additionally, the selection process did not consider practical constraints such as financial limitations or capacity requirements. Future research could focus on developing mathematical models that incorporate budgetary and capacity constraints to support more realistic and applicable decision-making.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. Additionally, ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been fully observed by the authors.

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