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# Innovative Procedures and Tools for the Digitalisation of Management Construction Processes in PA: A Systematic Scoping Review

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## Abstract

In recent years, the construction sector has experienced a significant technological transition, driven by the introduction of innovative digital tools and the evolution of the legislative environment. This article presents a Systematic Scoping Review conducted in accordance with the PRISMA-ScR guidelines, aiming to examine the role of Public Administration (PA) regarding the adoption of innovative technologies, such as Building Information Modelling (BIM) and Digital Twin (DT), to improve the management of construction and public procurement processes. The review analyses the state of the art in the implementation of digitalised procedures for project management in the construction phase, according to PA organisational purposes and national and international standard requirements. The data obtained was used to structure the analysis in order to provide a useful framework for understanding the level of convergence between the academic world and public administration in the use of digital technologies and their combined applications. The review results are organised in a thematic matrix classifying contributions according to key topics, building process phases, and operational aims. This approach highlights adopted strategies and emerging best practices, aiming to support both PAs and professionals in overcoming digitalisation challenges. A specific focus has been dedicated to the need for continuous training and legislative adaptation, which are essential for integrating digital technologies into building processes. The analysis and verification of the results of the systematic scoping review on the digitalisation process in the construction sector, conducted between academia and the public administration, is supported by a comparison with an Italian case study from the Emilia-Romagna region, which illustrates the specific application of the strategies identified in the digital management of public construction processes.

**Keywords:** public administration; construction site; digitalization; innovation technologies; project management; BIM; digital twin; scoping review; enabling technologies



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## 1. Introduction

In recent years, digitalisation has emerged as a strategic global priority within the construction sector, aiming to enhance operational efficiency, promote sustainability, and increase transparency throughout project management and delivery processes. This urgency has been explicitly highlighted in policy documents such as the European Commission's Digitalisation Strategy for the Construction Sector [1], which calls for the integration of digital tools to foster innovation and sustainable development. Numerous countries and international organisations are implementing targeted policies and funding programmes to encourage the integration of digital technologies in the built environment, reflecting a widespread global drive towards innovation [2].

The integration of digitalisation in the construction industry is increasingly viewed as part of an interconnected system, in which the adoption of a specific technology is closely linked to the development and dissemination of other digital solutions. This interconnected approach has been referred to as the twin transition, combining digital and ecological transformations, as emphasised in recent EU policy reports [3]. For this reason, digital strategies require a holistic approach that accounts for the interdependencies among technological tools and is adaptable to the regulatory, cultural, and market-specific conditions of different national contexts. Studies conducted by Deloitte [4] emphasise the importance of moving beyond a fragmented approach, advocating instead for an integrated and synergistic digital ecosystem capable of ensuring interoperability and continuity across the various platforms adopted within the construction sector [5].

Although Table 1 illustrates a growing number of national regulatory reforms aimed at digitalising procurement processes, these initiatives reveal significant variability in scope, implementation timelines, and technological integration across countries.

**Table 1.** Adoption of regulatory reforms for the digitalisation of public procurement processes.

| | | |
|---|---|---|
| Italy | 2023–2024 | Entry into force of the new Public Procurement Code (Legislative Decree No. 36/2023), effective from July 2023 and fully applicable from January 2024, mandates the full digitalisation of the public contract lifecycle, the use of electronic catalogues, and interoperability between platforms through the Public Contracts Platform [6]. |
| Germany | 2017 | Implementation of the XVergabe standard to ensure interoperability among various e-procurement platforms and the full digitalisation of procurement procedures. |
| UK | 2023 | Approval of the Procurement Act 2023, which introduced a centralised digital platform for public procurement management, streamlining access and participation for suppliers and buyers. |
| The Netherlands | 2023 | Implementation of the annual plan for the digitalisation of public procurement, featuring the adoption of interoperable platforms such as Tenderned and the utilisation of the Peppol network for information exchange. |
| Sweden | 2019 | Launch of the "Digital First!" reform to modernise the public sector, with the adoption of Peppol BIS standards for e-procurement and the promotion of interoperability between systems. |

**Table 1.** *Cont.*

| | | |
|---|---|---|
| Danmark | 2019 | Implementation of Peppol-based e-procurement solutions, promoting interoperability and the use of electronic catalogues to streamline public procurement. |
| Norway | 2019 | Adoption of national standards compatible with Peppol for e-procurement, facilitating interoperability and efficiency in public procurement processes. |

Notably, some Northern European countries (e.g., Sweden, Denmark, Norway) have adopted centralised and interoperable platforms, often aligned with the Peppol standard, promoting seamless data exchange and procurement efficiency.

In contrast, countries such as Italy, Germany, and the United Kingdom have pursued more decentralised or proprietary approaches, with varying levels of interoperability and strategic alignment.

This divergence underscores the persistence of a heterogeneous landscape and highlights the need for a coordinated strategic vision to ensure coherent and scalable digital adoption across Public Administrations.

### *1.1. The Role of the Public Administration (PA)*

At the international level, several governments have initiated regulatory reforms aimed at digitalising public procurement processes, introducing innovative tools such as electronic catalogues, standardised information workflows, and interoperability between digital systems, as illustrated in Table 1 [7]. Such reforms are consistent with recommendations of the European Commission promoting digital governance and transparency in public procurement to deliver high-quality services [8].

These measures prove essential to ensuring efficiency and transparency in public contracts. In Europe, particularly in the Nordic countries and other Member States, recent reforms demonstrate an increasing commitment to interoperable platforms for e-procurement [9]. Similar initiatives are observed globally, for instance in Canada and Singapore, reflecting a broader trend toward digital governance in public construction projects [10,11]. Simultaneously, in North America and the digitally advanced economies of the Asia-Pacific region, there is a consolidation in the adoption of digital platforms, aligning with the broader global acceleration of technological transformation [12].

Supporting this transition, numerous international investment programmes, such as Horizon Europe, Digital Europe, the United States National Institute of Standards and Technology (NIST), and initiatives promoted by the World Bank in emerging countries, aim to support research, development, and the adoption of digital technologies within the construction sector [13,14]. These programmes explicitly encourage the integration of BIM, DT, IoT, and AI to foster innovation and sustainability in public construction.

However, the adoption of digital technologies within Public Administrations (PA) still presents a heterogeneous and complex landscape. The strategies implemented vary significantly from country to country, reflecting differing national priorities, levels of technological maturity, and local administrative structures [15]. This diversity makes coordination at the supranational and intergovernmental levels essential to ensure a coherent and sustainable digital transformation. Despite international efforts and available funding, digitalisation in the construction sector faces numerous operational and cultural challenges. For this transformation to result in an actual improvement in the quality and efficiency of public services, profound changes in the organisational models of Public Administrations (PAs) are also required. Technologies alone are insufficient; a strategic vision is necessary, supported by a robust regulatory framework and sustained commitment to training and the adoption of digital operational models [5].

In this context, Public Administrations (PAs) play a pivotal role in driving the digital transition of the construction sector, especially through the digitalisation of public procurement processes and the implementation of interoperable platforms. However, while the global commitment to digital innovation is growing, the level of adoption and effectiveness of these strategies across PAs remains highly uneven and fragmented.

### *1.2. Barriers and Opportunities in Digital Transformation*

A 2018 survey conducted by KPMG revealed that only 23% of Chief Information Officers in the construction and engineering sector, both public and private, reported having a well-defined digital strategy, compared to 32% observed in other industries [16].

While this data illustrates a persistent legacy gap, the more recent KPMG Global Tech Report 2024, surveying 118 public-sector technology executives, shows that 85% are now prioritising emerging technologies over legacy systems, although two-thirds report lacking the talent needed to implement their digital transformation plans [17].

In response to these challenges, the present study conducts a systematic review of the international scientific literature, aiming to analyse the state of digitalisation in the construction sector, with particular focus on the role of Public Administrations (PA). The objective is to identify the main trends, strategies adopted to overcome barriers to innovation, and the remaining challenges. Through this analysis, the study intends to provide a comparative framework that is useful for defining more effective, sustainable, and replicable digitalisation models across diverse geographical contexts. This approach aligns with recent systematic reviews in the field, which emphasise the need to connect academic research with practical implementation in PAs [18,19].

The delay in adopting digital technologies in the construction sector, including limited interoperability, regulatory fragmentation, and skill gaps, hinders the integration of digital tools into public procurement and construction workflows. These structural obstacles have been consistently discussed in prior studies on digital transformation in construction and public administration [20,21].

Notably, the IDC report "The Future of Connected Construction" (2010) [22] identified five major challenges that remain highly relevant for Public Administrations today. These include the lack of a shared technological roadmap, difficulties in building scalable and interoperable digital architectures, and the absence of standardised KPIs to measure the impact of digitalisation.

Further challenges concern the limited availability of digital skills within public bodies and the slow integration of emerging technologies—such as IoT, Digital Twins, and AI—into operational and administrative workflows. Although some tools, like BIM, are now widely adopted, others such as Blockchain and robotics remain confined to experimental or research-driven implementations, with only partial uptake in public procurement and asset management contexts.

### *1.3. Research Objectives and Article Structure*

Digital transformation in the construction sector represents a multi-level challenge involving technological infrastructure, organisational models, skills, and regulations. Although interest in adopting advanced tools such as BIM, DT, IoT, artificial intelligence (AI), and blockchain is steadily increasing, their implementation by Public Administration (PA) remains heterogeneous and fragmented.

The main issues identified in the literature concern the lack of interoperability between platforms, regulatory fragmentation, insufficient digital skills, and the absence of a unified national strategic vision. In particular, the digital maturity of PAs varies significantly depending on the geographical and institutional context, limiting the scalability of best practices and the dissemination of replicable models.

In light of this scenario, the present study proposes a systematic review of the scientific literature, aiming to analyse the state of digitalisation in the public construction sector by identifying emerging trends, recurring barriers, and strategies adopted at the international level. Based on this perspective, the guiding research question of the present review is the following: *Is the digitalisation of Public Administrations aligned with the strategies and directions identified in the international scientific literature?* The analysis seeks to provide an updated and comparative overview of the role of PA in promoting digital innovation, identifying enabling factors and necessary conditions for an effective transition. This question provides a clear analytical direction and allows for a structured comparison between the academic literature and the practices implemented by PAs. The explicitation of the research question within the introduction to the scoping review provides consistency and supports the classification of articles and the case study examined, which are fundamental to understanding the digital transition in construction processes managed by public administration. This formulation is in line with the PCC framework recommended for scoping reviews, in which the Population (P) is represented by public administrations in the construction sector, the Concept (C) is digitalisation (technologies, procedures, barriers and strategies), and the Context (C) refers to both the international and national perspectives on public construction processes, with a specific focus on the Italian case study of Emilia-Romagna [23].

To this end, the reviewed contributions have been classified according to a thematic matrix structured by key topics, phases of the construction process, and operational objectives. This approach allows for the assessment of maturity levels and applicability of different technologies across the entire lifecycle of public works, from design to management and maintenance.

The conducted analysis intends to support public decision-makers, professionals, and researchers in defining more effective digitalisation strategies focused on public value, sustainability, and interoperability among systems and stakeholders. In particular, it highlights areas requiring greater regulatory, organisational, and training investments to overcome current obstacles and consolidate an integrated digital ecosystem within the public construction sector.

The paper is organised as follows: Section 2 introduces the methodological approach applied, while Section 3 shows the results of applying this method; Section 4 focuses on the comparison of the previous section with the case of an Italian PA, and Sections 5 and 6, respectively, address the discussions of the results obtained and the final conclusions.

## 2. Methodological Approach

The objective of this literature review is to examine the evolution of digitalisation within PA in the construction sector, focusing on identifying the main technologies adopted, implemented procedures, and regulatory protocols in place. No specific review protocol was registered for this scientific literature review. The review was conducted in accordance with the PRISMA-ScR guidelines, and a structured methodology was adopted to guide the selection and analysis of data in a progressive and targeted manner.

For this Systematic Scoping Review, no formal critical appraisal of the studies reviewed was conducted. In fact, the aim of this review is to outline the scope and characteristics of the existing evidence and not to evaluate the methodological rigour of each selected paper. This approach is in line with the PRISMA-ScR guidelines, which consider critical assessment optional for scoping reviews. The completed PRISMA-ScR checklist is provided in Appendix A, Figure A1 [24].

### *2.1. Criteria for Analysis and Structuring of the Literature*

To ensure a systematic and thorough analysis of digitalisation in the construction sector, with particular focus on the role of PA, the selected literature was organised into three macro-categories. The rationale for selecting these three macro-categories is rooted in both methodological and theoretical considerations. According to the framework for scoping reviews proposed by Arksey and O'Malley (2005) [25] and further refined in the PRISMA-ScR guidelines [24], it is essential to classify evidence along thematic domains that capture both the technological and organisational dimensions of a phenomenon. This classification facilitates the identification of the main research areas and fields of greatest development, facilitating a structured comparison among the different sources:

- **Digitalisation in PA:** This section focuses on analysing the role of PA in adopting digital tools to improve operational efficiency and transparency in administrative processes. It examines the digitalisation strategies implemented by governments, innovation policies applied to public procurement, and key regulatory initiatives that have incentivised the deployment of digital technologies in the public sector. Furthermore, it analyses the evolution of digitalisation in public management processes, assessing the level of technology adoption and the remaining barriers.
- **Digital technologies applied to construction**: This category focuses on technologies specifically applied to the construction sector, with particular emphasis on the implementation of BIM and DT in public works. The analysis considers the level of diffusion of these technologies, their interoperability with national and international regulatory standards (ISO 19650 [26], UNI 11337 [27]), and the potential they offer for efficient construction management [28]. A central aspect is the study of digital platforms that enable data sharing across the different stages of the project lifecycle [29], contributing to increased automation and resource optimisation.
- **Procedures and protocols for digitalisation:** This category examines the regulatory standards and guidelines adopted in various countries to govern the use of digital technologies within PA and the construction sector. The analysis focuses on best practices implemented in the digitalisation of public procurement processes and the regulatory instruments aimed at ensuring the security and transparency of procedures. Particular attention is given to standardisation policies and interoperability protocols that enable the integration of new technologies into construction and administrative processes.

### *2.2. Literature Selection Process*

To ensure an accurate and systematic analysis of digitalisation in the construction sector, with particular focus on the role of PA, a structured methodology was adopted to identify, select, and analyse the most relevant scientific contributions. The objective was to explore the evolution of digital technologies and their impact on administrative and operational processes, as well as the associated documentation and related regulatory and managerial implications connected to their implementation.

#### 2.2.1. Preliminary Analysis and Selection of the Keywords

Prior to finalising the keywords to be employed in the research, a preliminary analysis was conducted to identify the most effective terms to describe the phenomenon of digitalisation in the construction sector and within PA. This exploratory phase was carried out using the Scopus database, testing various keyword combinations, including synonyms, acronyms, and terminological variants, to assess their ability to yield relevant results.

The objective of this phase was to understand the breadth of coverage of each term. The analysis revealed that generic terms such as *Construction* or *Digitalisation* returned an extremely high number of results, whereas more specific combinations, such as *Public Administration AND BIM*, reduced the overall number of documents but improved the relevance of the identified content.

This preliminary evaluation allowed the identification of the most representative keywords and refined the search strategy, ensuring a balance between coverage breadth and the relevance of the results obtained.

To guarantee a comprehensive investigation and identify pertinent and related studies, an advanced search strategy was adopted, based on the use of synonyms, acronyms, and terminological variants combined through Boolean operators and wildcards. This approach enabled the expansion of the search field and inclusion of articles that, while addressing relevant topics, employ different terminologies to describe analogous concepts. The operator "OR" was used to consider terminological variants of the same concept, such as "Building Information Modelling" and its acronym "BIM", or "Digital Twin" and its abbreviation "DT". The inclusion of these alternative terms allowed the capture of a higher number of publications, ensuring broader coverage of the existing literature.

Subsequently, to identify intersections between topics of interest, the keywords were combined using the operator "AND", thus isolating studies that simultaneously address concepts such as BIM and DT, applied to digitalisation in the construction sector and PA.

For example, a search in the Scopus database using solely the term "Building Information Modelling" over a 20-year timeframe yielded 12,132 documents. However, including the acronym "BIM" significantly increased the number of documents identified, reaching 25,018.

Additionally, to include both singular and plural forms of some key terms without manual specification, the asterisk (*) wildcard was employed. This symbol further broadens the search results by automatically including all variants of a word. For instance, the query "process" retrieves documents containing "process", "processes", and "processing", thereby avoiding the need to list each possible variant manually.

This approach demonstrates how the combined use of Boolean operators and wildcards significantly improves the effectiveness of the search, allowing for a larger, more representative, and relevant dataset aligned with the study's objectives. Furthermore, the adopted methodology ensures the replicability of the process, contributing to enhancing the rigour and transparency of the conducted analysis.

#### 2.2.2. Sources and Timeframe

The research was conducted using the Elsevier Scopus database, one of the most authoritative sources of scientific literature, selected for its broad disciplinary coverage and the quality of indexed content.

The reference period for the search was set between 2014 and 2024, a timeframe chosen to capture the most recent developments in the field of digitalisation, considering that the adoption of advanced digital tools such as BIM and DT has significantly accelerated over the past decade, in parallel with the introduction of new European and national regulations.

#### 2.2.3. Considered Disciplines

To ensure comprehensive coverage, the literature search was conducted across multiple disciplinary domains, including engineering, architecture, computer science, management, and public administration studies. These areas were identified as particularly relevant to the digitalisation of construction processes in the public sector. Within each domain, specific keywords (e.g., "BIM", "Digital Twin", "Procurement", "Public Administration", "Construction Management") were applied in Scopus and Web of Science, allowing us to capture both the technological dimension of digital innovation and the organisational, managerial, and regulatory perspectives. This multidisciplinary approach ensured that the review included not only technical contributions but also studies addressing governance, policy, and implementation issues that are central to the digital transition in Public Administrations.

To ensure a multidisciplinary analysis, studies from various disciplinary fields were included, such as the following:

- **Engineering:** to examine the technical aspects of digitalisation in the design, construction, and management processes of public works.
- **Computer Science:** to analyse the digital technologies applied to the sector, such as AI, Machine Learning, IoT, and Blockchain.
- **Environmental Sciences:** to understand the impact of digitalisation in terms of sustainability, energy efficiency, and resource optimisation.
- **Business, Management, and Accounting:** to evaluate management models adopted in the digitalisation of the PA, with particular reference to public procurement and digital procurement strategies.
- **Decision Sciences:** to investigate governance models and decision-making processes related to the adoption of digital technologies in public construction.
- **Multidisciplinary:** to ensure a holistic view of the phenomenon, integrating studies from different sectors and research fields.

#### 2.2.4. Inclusion and Exclusion Criteria

In the selection of articles, only scientific articles and conference proceedings were considered, as they represent the main sources of up-to-date academic and scientific contributions on the topic. Other types of documents, such as reviews, editorials, and policy reports, were excluded to maintain focus on studies supported by validated analyses and methodologies (Table 2).

**Table 2.** Selected filters on Scopus.

| | |
|---|---|
| **Subject area** | • Engineering<br>• Computer science<br>• Environmental<br>• Business, Management and Accounting<br>• Multidisciplinary<br>• Decision Science |
| **Year range** | 2014–2024 |
| **Language** | • English<br>• Italian |
| **Document type** | • Article<br>• Conference Paper |
| **Open access** | All Open Access |

The search strategy was based on three key elements: keywords, abstracts, and article titles. This approach enabled the identification of highly relevant publications while avoiding articles that only marginally addressed the topic. A language filter was also applied, including only articles in English and Italian, to ensure clear comprehension of the content and greater consistency in the data analysed.

An additional selection criterion concerned article accessibility: Open Access studies were preferred to promote transparency and the dissemination of information without financial or editorial barriers. This choice was driven by the need to ensure full access to the analysed documents, facilitating direct comparison and independent verification of results.

### *2.3. Classification and Validation Criteria for the Analysed Literature*

After identifying the relevant literature and selecting articles based on the methodological criteria described in the previous sections, a subsequent classification was carried out to ensure a coherent structure of the analysis. This process made it possible to organise the studies in a way that facilitates comparison across different disciplinary perspectives and to identify emerging trends in the context of digitalisation in the construction sector and within the PA. The classification of the articles was conducted according to three fundamental criteria:

A. **Relevance to the Selected Literature***:* only articles directly addressing the topic of digitalisation in PA and the construction sector were included, excluding studies with a marginal focus or not closely related to the subject.
B. **Number of Citations**: to identify studies with higher scientific and academic impact, articles with a significant number of citations were selected, as this is an indicator of their relevance within the scientific debate.
C. **Elimination of Duplicates**: to avoid redundancies, articles found in multiple databases or presenting overlapping content were removed.

The categorisation of the articles made it possible to identify the most developed areas of research while also highlighting those in need of further consolidation. This approach provided a clear overview of the state of the art of digitalisation in the PA and the construction sector, offering valuable insights for the development of future strategies aimed at bridging existing gaps and promoting a more effective integration of digital technologies.

### *2.4. Matrix Setup*

The developed matrix collects and analyses a set of contributions related to the use of digital technologies in the construction sector, with the aim of highlighting emerging trends, prevailing methodological approaches, the stages of the construction process involved, the objectives pursued through digitalisation, and the technological capabilities actually implemented.

Each row of the matrix corresponds to a single scientific article and includes the following descriptive fields:

A. **Article Identifier (ID Paper):** a unique code assigned to each analysed contribution, useful for tracking and referencing.
B. **Case Study Type**: specifies the main application context of the analysed case, distinguishing between infrastructures, buildings, or urban areas.
C. **Approach Type**: describes the methodological nature of the contribution, classifying the article as a literature review, methodological study, or applied study.
D. **Involved Construction Process Phases**: The Public Contracts Code (Legislative Decree 31 March 2023, No. 36) clearly identifies the main phases of the public work lifecycle, breaking them down into the following:
    - *(d.1)* *Programming:* the preliminary phase in which PAs define needs, intervention priorities, and allocate financial resources. Programming includes drafting strategic guidance documents and requirement frameworks.
    - *(d.2)* *Design: each level aims at the progressive technical, economic, and* functional definition of the work.

(d.3) *Execution*: the phase in which the awarding and construction of the work take place. It includes the contract signing, site commencement, technical and economic control of the execution, and any variations during construction.

(d.4) *Facility Management:* the post-construction phase includes all activities related to monitoring, routine and extraordinary maintenance, operational management, and performance control of the infrastructure or building.

E. **Scopes of the digitalisation**: In the construction sector, the objectives of digitalisation mainly revolve around four fundamental directions. This trend is widely confirmed by numerous recent studies, highlighting a growing focus on process efficiency, automation, risk management, and the promotion of collaboration among involved stakeholders.

In 2017, Deloitte, in its report "Digital Construction: From Vision to Reality", emphasised how the adoption of digital technologies such as BIM and augmented reality aims to increase productivity, reduce execution errors, and improve collaboration among project participants (see Table 3). The report also highlights the role of digital tools in supporting rapid and effective decision-making through greater visibility of project data, thus contributing to risk management and cost control [5].

Similarly, the 2020 IDC and Autodesk report underscores the strategic value of digitalisation in promoting operational efficiency and process standardisation, encouraging greater automation and interoperability between adopted platforms. Additional objectives identified include enhancing business resilience, ensuring the availability of real-time information, and adopting digital metrics for performance evaluation [22].

Both sources converge on the urgency of an integrated approach focused on system interconnection, data quality, and strengthening the digital skills of sector professionals.

**Table 3.** Comparison of digitalisation objectives according to Deloitte and IDC-Autodesk.

| *Scopes of the Digitalisation* | *Deloitte (2017)* [5] | *IDC and Autodesk (2020)* [22] |
|---|---|---|
| Operational efficiency | Increased productivity; reduction in time and errors | Increase in efficiency and productivity |
| Process automation | Use of technologies to streamline operational activities | Standardisation, automation, and simplification of operations |
| Risk and cost management | Decision support through real-time data and financial transparency | Data-driven decision-making; proactive risk management |
| Collaboration and transparency | Information sharing among project stakeholders | Integration and interoperability among platforms and stakeholders |
| Resilience and business continuity | (Mentioned within the context of digital collaboration) | Improvement of organisational resilience and complexity management |

The objectives of digitalisation in the construction sector primarily focus on five key areas [22]:

(e.1) *Automation:* reduction in manual tasks through software, algorithms, or intelligent technologies; aimed at increasing productivity and minimising human error.

(e.2) *Efficiency improvement:* enhancement of energy, operational, and managerial efficiency through the optimisation of resources, time, and costs.

(e.3) *Transparency and Traceability:* the ability to continuously monitor and document activities, decisions, and information flows throughout the building lifecycle in an accessible manner.

- *(e.4)* *Risk and Cost Management:* the use of predictive tools, simulations, and analytical methods to prevent critical issues and proactively assess the impact of decisions.
- *(e.5)* *Collaboration:* enhancement of coordination among supply chain stakeholders through shared workflows, interoperability, and integrated access to information.

F. **Implemented Technological Capabilities**: The technological capabilities analysed in the case studies were classified according to the model proposed by the Digital Twin Consortium, which identifies six functional categories:

- *(f.1)* *Data Services (DS):* This category includes capabilities related to data access, ingestion, and management across the platform, from the edge to the cloud. It includes services for data integration, basic and advanced analytics, artificial intelligence, orchestration, and other Digital Twin process functionalities.
- *(f.2)* *Integration (IR):* It refers to the capabilities that enable data access from existing internal and external enterprise systems and applications, facilitating communication between different Digital Twins.
- *(f.3)* *Intelligence (IC):* It includes capabilities that provide an environment for the development and deployment of industrial Digital Twin solutions, offering services for data integration, advanced analytics, artificial intelligence, orchestration, and other Digital Twin process functionalities.
- *(f.4)* *User Experience (UX):* It encompasses the capabilities that enable users to interact with Digital Twins and visualise their associated data.
- *(f.5)* *Management (MN):* It refers to system and ecosystem management capabilities, ensuring that all components of the Digital Twin operate in a coordinated and efficient manner.
- *(f.6)* *Trustworthiness (TW):* It includes capabilities related to security, privacy, reliability, and resilience, ensuring that the Digital Twin operates securely and in compliance with regulations.

For each article, a qualitative level of technological implementation was assigned, represented through a traffic light coding system. This visual approach summarises the degree of maturity and actual application of the digital technologies discussed. Specifically:

- *Green—clear and operational application:* the technology is thoroughly described and effectively employed in the analysed case study, with concrete examples of implementation.
- *Yellow—limited presence or mentioned*: the technology is referenced in the text, but its use is marginal, unsystematic, or not supported by practical application.
- *Red—absent or not relevant*: there is no significant reference to the technology, or it is not pertinent to the content discussed.

This coding system enables a rapid mapping of the prevalence and maturity level of different technological capabilities within the case studies, facilitating the identification of gaps, best practices, and potential areas for future development in the digital construction sector. To synthesise the evidence, the charted data were aggregated thematically and analysed in terms of frequency. Contributions were grouped according to research topic, stage of the construction process, operational objectives, and enabling technologies, with the results presented in Section 3 (Analysis of Results and Definition of the Thematic Matrix).

### *2.5. Article Selection*

The application of the selection methodology described in the previous section led to the identification of an initial corpus of 557 articles (see Figure 1). These were subsequently classified into thematic categories to ensure a structured and coherent analysis of the digitalisation process in the construction sector, with a specific focus on the role of PA.

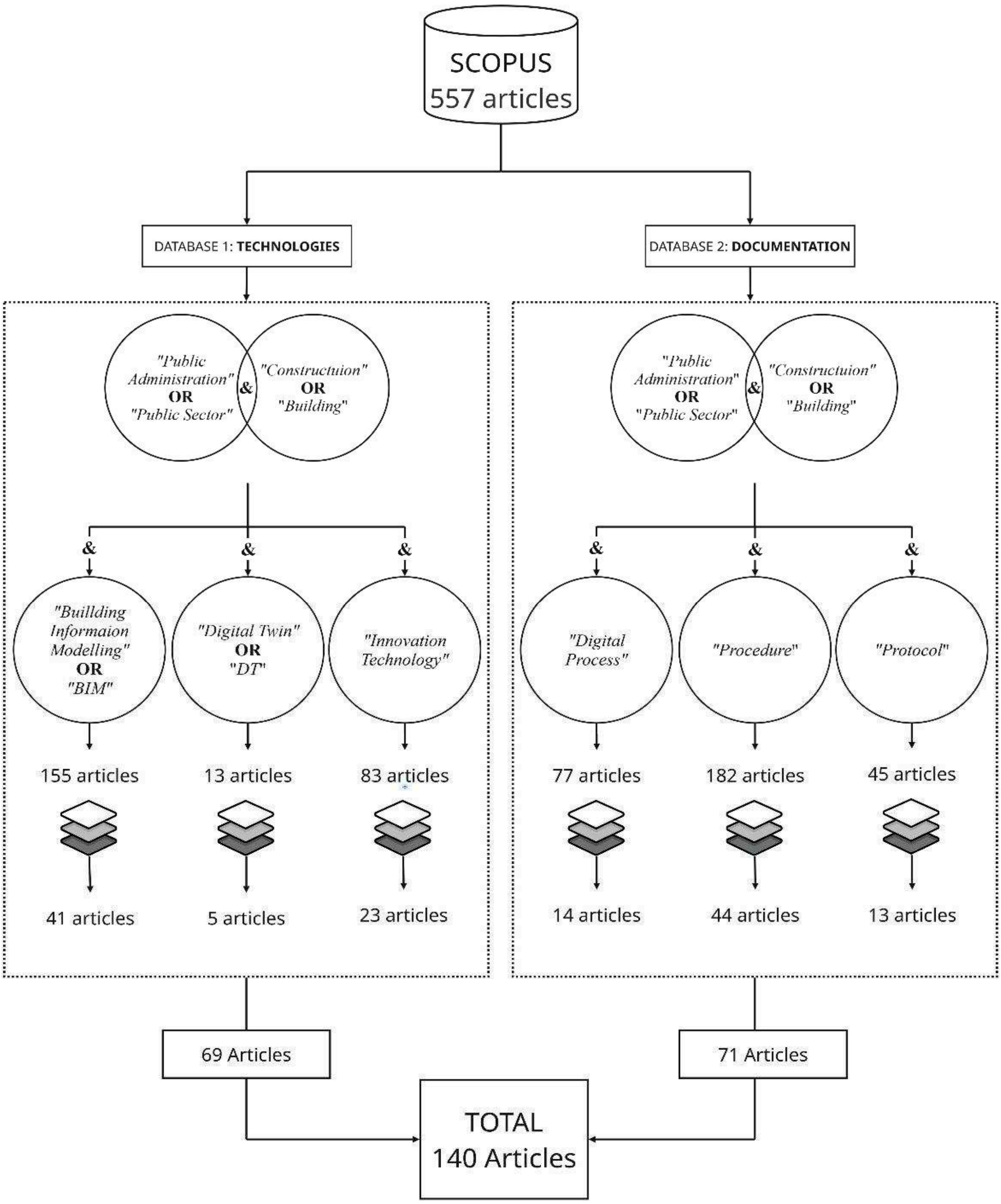


**Figure 1.** PRISMA-ScR flow diagram to obtain the final list [30–169].

To facilitate a systematic investigation and highlight the main areas of digitalisation development, the selected articles were divided into two macro-categories:

A. *Digitalisation Technologies (251 articles)*: This category includes studies analysing the implementation and use of digital technologies within the public sector and construction industry. The main topics addressed include:

- **155 articles** related to Building Information Modelling (BIM), one of the most established technologies for digital modelling and management of construction projects.

- **13 articles** on Digital Twin (DT), an emerging technology enabling the creation of virtual replicas of buildings and infrastructure for real-time monitoring and management.
- **83 articles** on other innovative digital technologies (Innovation Technology), including Internet of Things (IoT), Blockchain, Artificial Intelligence, and advanced automation systems applied to the digitalisation of the public sector and construction.

B. *Documentation of the digitalisation (304 articles)*: This category collects studies examining the regulatory framework, administrative processes, and methodologies adopted by Public Administration to implement digitalisation in the construction sector. The analysed studies are subdivided into the following:

- **77 articles** on Digital Process/Processes, exploring digital processes implemented to improve efficiency in managing and organising activities within the Public Administration.
- **182 articles** on Procedures, which include operational methodologies, standards, and regulations applied to digitalisation processes in public procurement and construction management.
- **45 articles** on Protocols, analysing guidelines, rules, and regulatory frameworks developed to ensure secure and effective integration of digital technologies in public and regulatory processes.

After applying the selection criteria outlined in the methodology, the total number of analysed articles was reduced to 140. Figure 1 (and Figure A2) provides a graphical representation of the article screening process, illustrating how the initial set of 150 articles was narrowed down to 140 for the subsequent analysis, and highlighting the two main thematic clusters identified. The final distribution of selected articles, corresponding to over 25% of the initial corpus, is as follows:

- **69 articles** concerning digitalisation technologies, examining the maturity level and diffusion of innovative tools within public construction.
- **71 articles** relating to regulatory and procedural documentation, analysing the implementation methods of digitalisation at the administrative and regulatory levels.

This final selection enabled a concentration on the most significant and academically impactful studies, providing a clear and up-to-date overview of the state of the art in digitalisation within Public Administration and the construction sector. The results outline both established trends, such as the widespread use of BIM and the increasing standardisation of digital processes, as well as emerging challenges, including the adoption of Digital Twin technology and the integration of advanced technologies like Blockchain and Artificial Intelligence into public management and procurement processes.

### *2.6. Geographical Distribution of the Analysed Articles*

The analysis of the articles indicates that Italy, the United Kingdom, and Spain are the leading countries producing research in the field of digitalisation applied to industrial processes and technologies. Figure 2 shows a global and European geographic map in which the intensity of the colour for each country corresponds to the number of publications, with darker shades indicating a higher publication volume. Italy stands out with 8 studies dedicated to Building Information Modelling (BIM), 2 on digital twin (DT), 1 on innovation technology (IT), 6 on processes (PROC), 2 on protocols (PROT), and 4 on digital procedures (DP). Figure 3 presents the thematic matrix, highlighting the number of articles produced by each country across the four selected themes, with colour intensity indicating higher publication volumes. This distribution reflects a balanced commitment between the development of digital methodologies and their practical application in process management, highlighting a robust research foundation that integrates technological and operational aspects. The United Kingdom presents a slightly different distribution, with 7 articles on BIM, 1 on digital transformation, 4 on innovation technology, 1 on processes, 1 on protocols, and 2 on digital procedures. This pattern suggests a strong interest in technological innovation and particular attention to the integration of new technologies with management processes, indicating a more experimental approach oriented towards the adoption of innovative solutions.

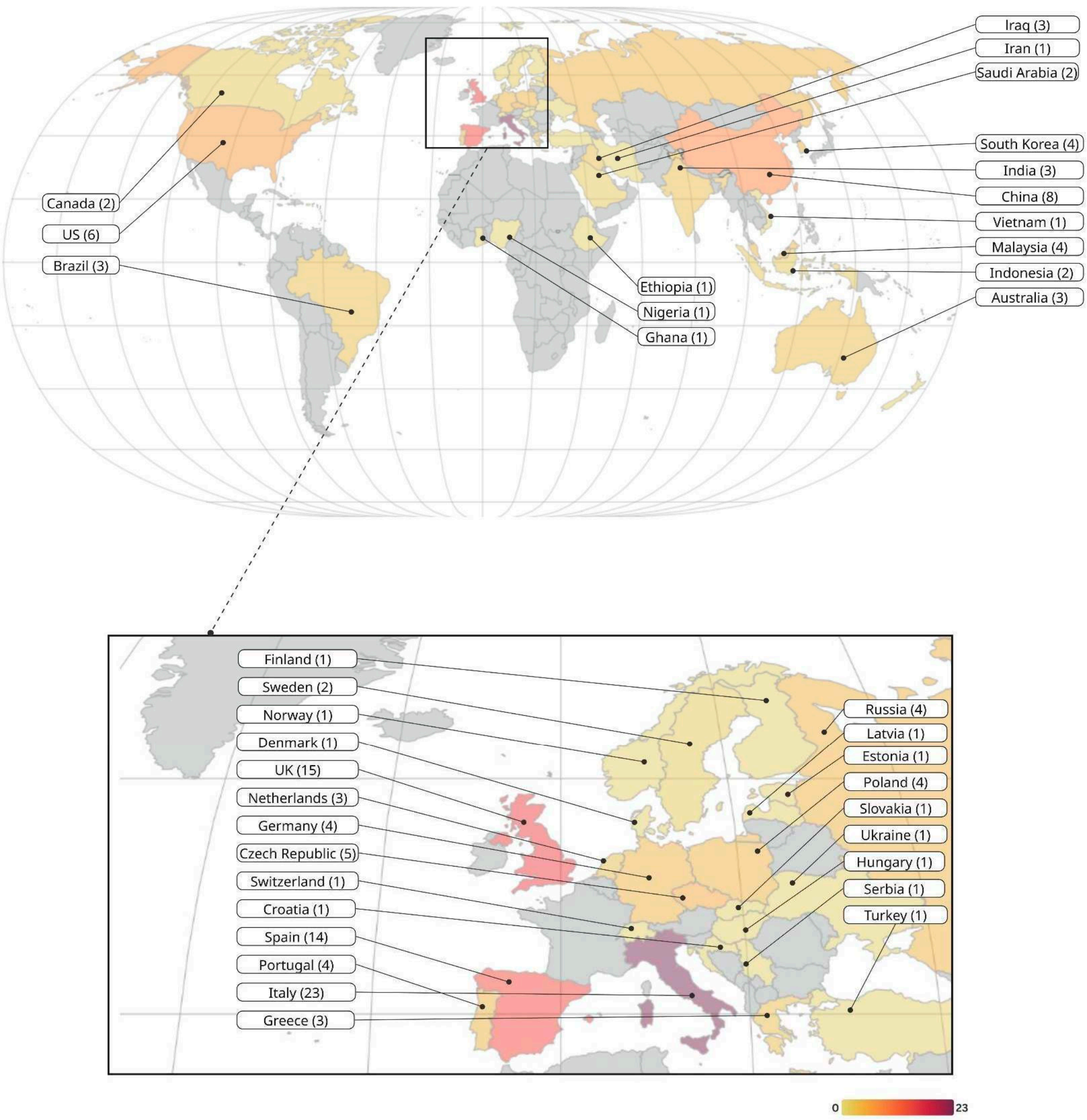


**Figure 2.** Global distribution of articles proportional to colour intensity.

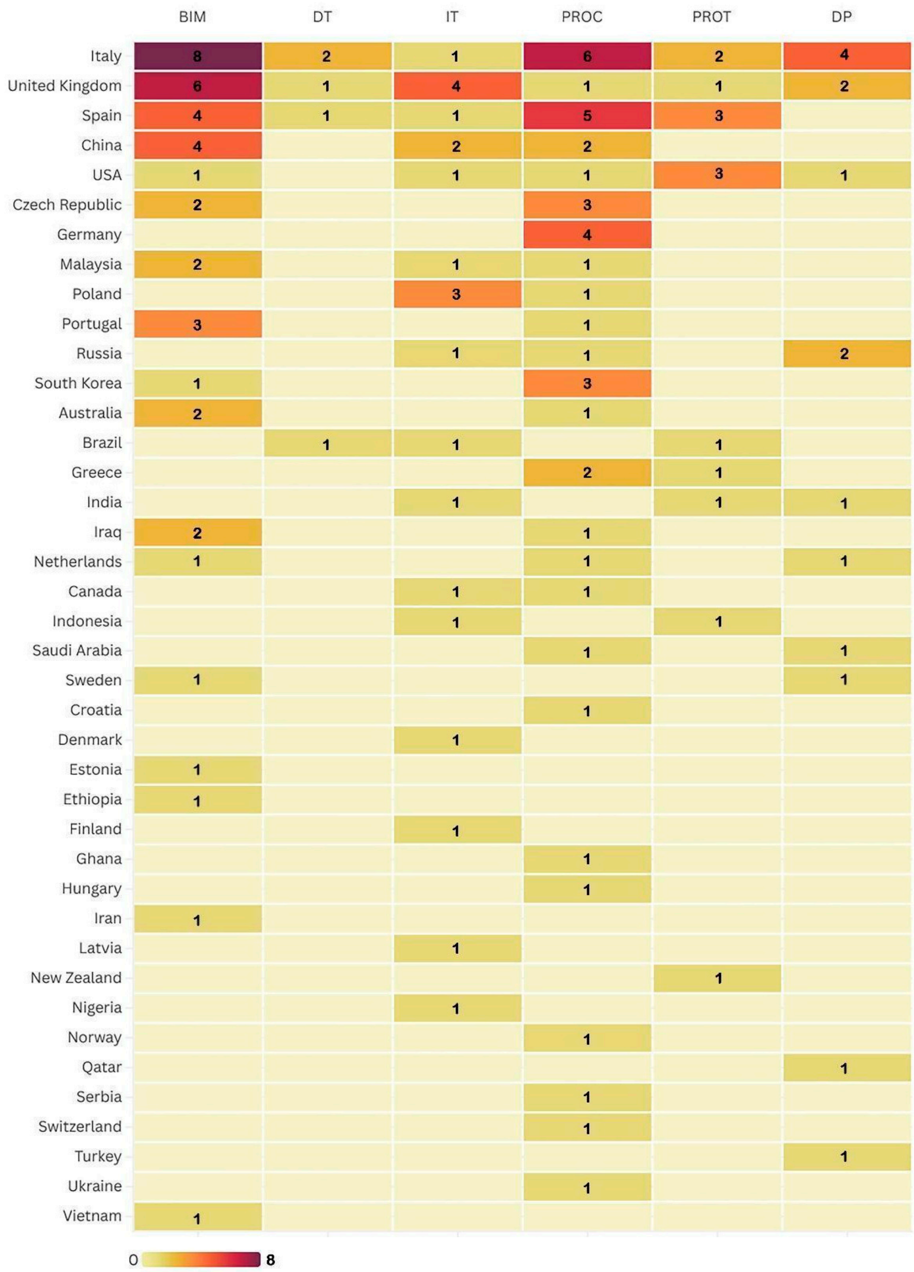


**Figure 3.** Global distribution of articles proportional to colour intensity and according to topic.

Spain, with 4 studies on BIM, 1 on digital transformation, 1 on innovation technology, 5 on processes, and 3 on protocols, demonstrates a pronounced focus on governance and digital regulation, likely reflecting a significant emphasis on structuring workflows and operational procedures, a crucial aspect for ensuring standardisation and replicability of digital solutions.

At the global level, thematic distribution shows that BIM and processes are the most studied topics, with 41 and 44 articles, respectively, followed by innovation technology (23), digital procedures (14), and protocols (13). However, it is important to highlight that 93 of the 140 analysed articles originate from European countries, underscoring Europe's leadership in research and development of digital technologies applied to industrial processes. This European predominance suggests strong investment and interest within the continent towards digital transformation, likely supported by favourable policies, European funding, and a well-established culture of technological innovation.

Outside Europe, scientific production is more fragmented and distributed across various countries, with significant contributions from nations such as China, the United States, Australia, and India. This geographical diversity also reflects differing stages of adoption and maturity of digital technologies across industrial and regulatory contexts, as well as varying research priorities.

The thematic and geographical differences may be interpreted in relation to national industrial and regulatory contexts that shape development priorities. For instance, Italy's strong presence in BIM and processes may stem from its construction and civil engineering traditions, whereas the UK's focus on technological innovation reflects the dynamic and competitive technological environment of the country. Spain, on the other hand, appears to be prioritising the development of protocols and standards, perhaps in response to the growing need for stricter coordination and control requirements.

In conclusion to this section, despite these differences, it is possible to confirm that a shared interest emerges in the integration of digital technologies and management processes, which could foster enhanced international collaboration and the development of shared best practices, laying the groundwork for a more effective and harmonised digital transformation at a global scale in the near future.

## 3. Analysis of Results and Definition of the Thematic Matrix

The analysis conducted on the selected contributions using the matrix highlights a series of significant trends in the evolution of digitalisation applied to the construction sector. In Figure 4, we introduce an extract of this matrix, where for each paper the case study type, methodological approach, phase of the construction process under investigation, and purpose of digitalisation have been identified, alongside the enabling technologies and a summary of the adopted strategy and emerging critical issues. Namely, as mentioned in the methodology section regarding technological capabilities, a colour-coded classification system was employed (as previously described at point 7 in Section 2.4).

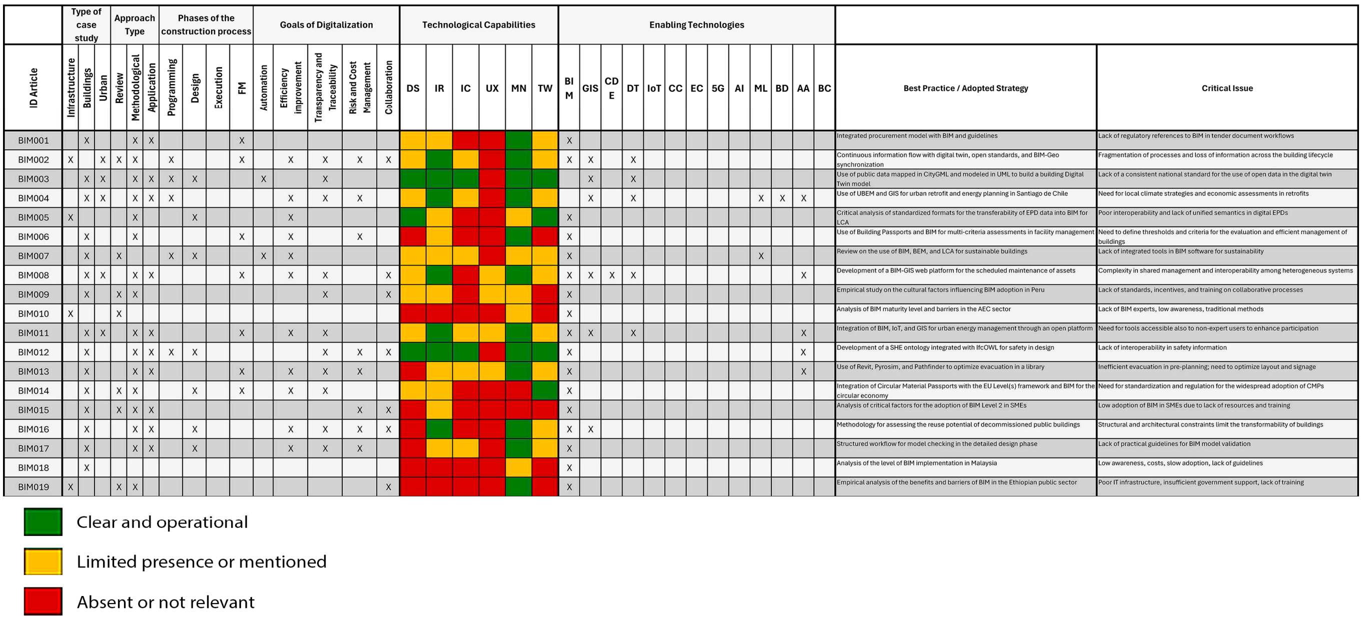


**Figure 4.** Extract from the matrix (Full matrix in Figure A3).

From a temporal perspective, there is a marked increase in publications starting from 2020, with a notable peak in 2024. This trend reflects the growing interest of the scientific community in digital technologies within the construction context, probably stimulated by national and supranational funding programmes.

Regarding the type of case study, the majority of contributions focus on buildings, followed by urban scenarios and, to a lesser extent, infrastructure. This suggests greater maturity and availability of data in the building construction sector compared to other domains.

Methodologically, there is a clear predominance of applied approaches, with numerous studies centred on direct experimentation and the concrete implementation of digital technologies in construction processes. This indicates a transition from the theoretical phase to the operational stage of digital transformation.

Analysing the phases of the construction process involved, design emerges as the stage most impacted by the introduction of digital tools, followed by facility management and execution. Initial planning, however, appears less explored, indicating potential scope for future development.

The most recurrent objectives of digitalisation are process optimisation and activity automation, while aspects related to risk and cost management receive less attention, despite their strategic importance.

Overall, the analysis confirms an increasing adoption of digital tools aimed at operational optimisation, while also highlighting persistent challenges such as poor interoperability among systems, the absence of shared standards, and the need for advanced technical skills among personnel involved. These factors represent significant barriers to full digital integration and call for targeted interventions at the regulatory, technical, and educational levels.

### *3.1. Enabling Technologies for the Digitalisation of the Built Environment*

The analysis of the current panorama reveals an acceleration in the adoption of digital tools within the construction sector, primarily focused on practical solutions aimed at enhancing streamlining and process automation (see Table 4). However, this digital transition faces significant challenges, including insufficient interoperability between systems, the lack of shared standards, and inadequate technical training among industry professionals.

In this context, so-called enabling technologies assume a central role. These are the technological components that must be integrated into digital systems to ensure their correct functioning, enable the intended features, and facilitate the achievement of project objectives. In order to systematically analyse the scientific literature on the digitalisation of construction, our method involved identifying the enabling technologies associated with each article and noting them in a dedicated column. This column captures both the technological solutions adopted and the technological capabilities these solutions enable.

Within the scope of construction digitalisation, it is crucial to distinguish between enabling technologies and technological solutions, as they play different roles within the digital ecosystem. Enabling technologies constitute the fundamental technological infrastructure—that is, the set of tools, platforms, and paradigms that make the implementation of advanced digital functionalities possible. These are cross-cutting components, often not directly visible in the final products but essential for activating specific operational and organisational capabilities. Notable examples include the IoT, Cloud Computing, AI, BIM, and edge computing.

However, technological solutions represent the concrete and contextualised application of one or more enabling technologies to solve specific problems or achieve particular goals within a project. They are systems, tools, or platforms developed based on enabling technologies and are generally perceived as the "operational interfaces" of innovation. For instance, a real-time energy monitoring platform can be considered a technological solution that leverages enabling technologies such as IoT sensors, cloud infrastructure, and data analytics.

**Table 4.** Enabling technologies and technological solutions have been identified in the scientific literature.

| Enabling Technologies | Technological Solutions |
|---|---|
| **Building Information Modelling (BIM)** | Revit, BIMReL, BIM + GIS integration, BIM + IoT, blockchain-enabled models, BIM plug-ins, model checking, 3DStock, Last Planner System, Design for Manufacturing and Assembly (DfMA) |
| **GIS** | BIM + GIS integration, WebGIS platforms, interoperable geodatabases, ArcGIS, ArcGIS Online, QGIS with custom plug-ins |
| **CDE** | ACDat, Autodesk Construction Cloud (ACC), Trimble Connect, shared document management systems, IFC interoperability, controlled stakeholder access, modification traceability |
| **Digital Twin (DT)** | Space management systems, predictive maintenance, VEWS platform, real-time sustainable monitoring |
| **Internet of Things (IoT)** | LoRa sensors, BLE virtual barriers, edge computing platforms, Digital Twin (DT) + BIM + IoT prototypes |
| **Cloud Computing (CC)** | Environmental monitoring applications, cloud-based document storage, and BIM–cloud integration |
| **Edge Computing (EC)** | Raspberry Pi, edge architectures for greenhouses, latency reduction, local data processing |
| **5G** | Smart city infrastructures, network slicing, ultra-low latency services |
| **AI** | Predictive systems, energy optimisation, facility management tools |
| **ML** | Pattern recognition, climate forecasting, operational flow optimisation |
| **Big Data (BD)** | KPI analysis, environmental data aggregation, urban planning |
| **Advanced Analytics (AA)** | Predictive simulations, visual analytics, fuzzy modelling, Soft Building Modelling (SBM), multi-criteria analysis |

Understanding this distinction not only allows for a clearer analysis of what has been adopted in case studies but also facilitates the evaluation of the quality and coherence of technological choices relative to project objectives. Enabling technologies, in fact, do not generate value on their own; rather, value is realised when they are integrated within technological solutions that fully exploit their potential.

Each enabling technology is correlated with technological capabilities based on the traffic-light coding observed in the analysed sources. Specifically, the inclusion of a dedicated section on enabling technologies and their associated technological capabilities allows for a direct linkage between design objectives and implemented solutions. This facilitates the rapid identification of effective technologies tailored to specific needs, such as interoperability, automation, artificial intelligence, data management, or user experience. In this regard, the matrix serves as an operational reference to guide informed decision-making, reduce technological uncertainty, and promote the coherent integration of digital components within construction processes.

The matrix presented in Figure 5 illustrates the frequency with which eleven enabling technologies have been associated with the six categories of technological capabilities defined by the Digital Twin Consortium: Data Services (DS), Integration (IR), Intelligence (IC), User Experience (UX), Management (MN), and Trustworthiness (TW). The data were extracted from a structured sample of case studies, analysed using a traffic-light coding scheme, and subsequently aggregated based on the recurrence of mapped technologies.

| | DS | IR | IC | UX | MN | TW |
|---|---|---|---|---|---|---|
| BIM | 16 | 32 | 13 | 5 | 39 | 23 |
| GIS | 3 | 9 | 2 | 3 | 6 | 1 |
| CDE | 8 | 6 | 1 | 0 | 2 | 1 |
| DT | 9 | 7 | 7 | 5 | 11 | 7 |
| IoT | 7 | 0 | 6 | 8 | 2 | 2 |
| CC | 8 | 0 | 0 | 11 | 0 | 9 |
| EC | 0 | 0 | 0 | 0 | 0 | 0 |
| 5G | 0 | 2 | 0 | 0 | 0 | 5 |
| AI | 1 | 0 | 5 | 2 | 3 | 2 |
| ML | 0 | 0 | 5 | 0 | 0 | 0 |
| BD | 29 | 8 | 4 | 8 | 5 | 12 |
| AA | 19 | 2 | 10 | 6 | 5 | 29 |
| BC | 0 | 1 | 0 | 1 | 1 | 7 |

**Figure 5.** Frequency of association between enabling technologies and technological capabilities in the analysed case studies.

By employing gradient colour conditional formatting, the most frequently adopted technologies within each capability category can be easily identified.

Among the enabling technologies considered, Building Information Modelling (BIM) stands out as the most widely adopted across categories, with particularly significant occurrences in Management (39), Integration (32), and Trustworthiness (23).

This emphasises the central role that building information modelling plays not only in the design phase but also in managing and ensuring the reliability and traceability of digital twins in the built environment.

Big Data (BD) and Advanced Analytics (AA) follow in terms of overall frequency. Big Data is strongly correlated with Data Services (29), while Advanced Analytics shows high associations with Trustworthiness (29), Data Services (19), and Intelligence (10). The prominence of these two technologies confirms the critical role of data processing and valorisation as cornerstones of integrated digital systems.

Digital Twin (DT) and Cloud Computing (CC) exhibit a more balanced distribution, with applications spanning Management, UX, and DS. This reflects the need for interoperable and accessible infrastructures for the effective management and exploitation of digital models.

Geographic Information Systems (GIS), though less frequent overall, demonstrate a noteworthy presence in Integration (9) and Management (6), suggesting their relevance in structuring spatial data and supporting location-based decision-making. Their role is especially pronounced in urban and infrastructure contexts, where geographic components are essential for the implementation of georeferenced digital models.

The Common Data Environment (CDE) shows specific relevance in Data Services (8) and Integration (6), consistent with its function as a collaborative environment for centralised data management and sharing. The value of CDE becomes especially evident in contexts where data reliability and document traceability are critical to the success of digital construction processes.

In contrast, some emerging enabling technologies—such as Edge Computing (EC) and Machine Learning (ML)—are either absent or scarcely represented. This points to a gap between their theoretical potential and actual adoption in the available case studies.

Similarly, technologies like 5G, Blockchain (BC), and Artificial Intelligence (AI) register marginal values, often limited to specific contexts. These limitations may stem from infrastructural, regulatory, or technological maturity barriers.

Overall, the matrix provides a clear snapshot of the current landscape of digital twin applications in the construction sector. It reveals a strong reliance on information modelling, data management, and process reliability technologies, while the adoption of intelligent, edge, or distributed solutions remains embryonic or context-specific.

This simply means that the future development of digital twins will require enhanced computational and communication capabilities to support greater autonomy, adaptability, and scalability of digital models.

The chart (Figure 6) illustrates the distribution of the main enabling technologies in relation to the four canonical phases of the construction process: Programming, Design, Execution and Facility Management (FM).

| | Programming | Design | Execution | FM |
|---|---|---|---|---|
| BIM | 10 | 26 | 6 | 18 |
| GIS | 6 | 5 | 1 | 6 |
| CDE | 4 | 7 | 4 | 3 |
| DT | 4 | 4 | 1 | 9 |
| IoT | 3 | 3 | 1 | 7 |
| CC | 10 | 2 | 2 | 7 |
| EC | 0 | 0 | 0 | 0 |
| 5G | 1 | 0 | 3 | 3 |
| AI | 4 | 2 | 0 | 5 |
| ML | 3 | 1 | 0 | 2 |
| BD | 15 | 9 | 10 | 16 |
| AA | 25 | 11 | 7 | 11 |
| BC | 3 | 2 | 1 | 2 |

**Figure 6.** Frequency of use of enabling technologies across the building process phases.

Among the technologies examined, Building Information Modelling (BIM) stands out with a markedly dominant presence in the design phase (26 occurrences), reaffirming its central role in information modelling and in the coordinated definition of building projects.

Data-driven technologies, particularly Big Data (BD) and Advanced Analytics (AA), are significantly associated with both the facility management phase (BD: 16; AA: 11) and the programming phase (BD: 15; AA: 25), indicating a growing focus on data-informed approaches in management and planning processes.

Digital Twin (DT) and the Internet of Things (IoT) exhibit a less pronounced yet cross-cutting presence, with applications distributed across multiple phases, particularly in facility management (DT: 9; IoT: 7), highlighting their potential in contexts characterised by high information and operational complexity.

Geographic Information Systems (GIS) also show a distributed usage throughout the entire construction process, with occurrences in programming (6), design (5) and facility management (6), confirming their relevance in geolocation, land management and the spatial representation of both design and operational information.

However, the Common Data Environment (CDE) is more concentrated in the design (7) and execution (4) phases, where it enables controlled and centralised access to information among stakeholders, contributing to the reduction in errors and the improvement of document traceability.

In contrast, emerging technologies such as Edge Computing (EC) are entirely absent from the matrix, suggesting a still marginal diffusion within the current construction sector. Similarly, the adoption of solutions based on 5G, Artificial Intelligence (AI), Machine Learning (ML), and Blockchain (BC) appears to be limited, reflecting either an early stage of adoption or confinement to highly specialised use cases.

The chart (Figure 7) highlights the correlations between enabling technologies and five strategic objectives of digitalisation in the construction sector, namely automation, collaboration, operational efficiency, risk and cost management, and transparency and traceability.

| | Automation | Collaboration | Streamlining | Risk and cost management | Transparency and traceability |
|---|---|---|---|---|---|
| BIM | 12 | 25 | 41 | 22 | 26 |
| GIS | 1 | 7 | 10 | 6 | 6 |
| CDE | 6 | 8 | 8 | 3 | 6 |
| DT | 5 | 4 | 11 | 8 | 7 |
| IoT | 6 | 3 | 8 | 5 | 3 |
| CC | 8 | 10 | 11 | 5 | 7 |
| EC | 0 | 0 | 0 | 0 | 0 |
| 5G | 3 | 1 | 4 | 4 | 1 |
| AI | 4 | 1 | 6 | 6 | 2 |
| ML | 2 | 1 | 4 | 3 | 2 |
| BD | 15 | 7 | 24 | 24 | 13 |
| AA | 6 | 9 | 23 | 27 | 16 |
| BC | 4 | 4 | 2 | 3 | 5 |

**Figure 7.** Frequency of use of enabling technologies for each purpose of digitalisation in the construction sector.

Building Information Modelling (BIM) emerges as the most widely applied enabling technology, with a peak in associations related to process optimisation (41 occurrences), followed by transparency and traceability (26 occurrences) and collaboration (25 occurrences). These results underline the cross-functional nature of BIM and its capacity to support process optimisation, waste reduction and the structured sharing of information throughout the asset lifecycle.

Alongside BIM, Big Data (BD) and Advanced Analytics (AA) are also prominent, with strong correlations to streamlining (BD: 24, AA: 23) and risk and cost management (BD: 24, AA: 27). Their widespread use reflects the emergence of predictive and data-driven approaches, which enhance decision-making and process control in construction.

Technologies such as Digital Twin (DT) and the Internet of Things (IoT) show a significant yet more evenly distributed presence, suggesting their application in complex or experimental contexts.

Geographic Information Systems (GIS) and Common Data Environments (CDE) also demonstrate relevant use, particularly for streamlining (GIS: 10, CDE: 8), transparency and traceability (GIS: 6, CDE: 6) and collaboration (GIS: 7, CDE: 8). These findings confirm the strategic role of GIS in the spatial representation and management of territorial data and of CDE as a shared environment for information coordination among construction stakeholders.

Conversely, Edge Computing (EC) does not appear in the matrix, indicating a still marginal adoption in the construction domain. Similarly, technologies such as Blockchain

(BC) and Artificial Intelligence (AI) show selective yet coherent applications, particularly in the domains of automation (BC: 4, AI: 4) and transparency and traceability (BC: 5, AI: 2).

Figure 8 presents the frequencies of co-occurrence between pairs of enabling technologies used across the case studies analysed. Each cell indicates the number of articles in which a given pair of technologies appears jointly, allowing the identification of operational synergies, integration trends, and recurrent adoption patterns.

| | BIM | GIS | CDE | DT | IoT | CC | EC | 5G | AI | ML | BD | AA | BC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BIM** | - | 6 | 5 | 7 | 3 | 1 | 0 | 2 | 3 | 2 | 5 | 6 | 2 |
| **GIS** | 6 | - | 3 | 5 | 0 | 1 | 0 | 0 | 0 | 1 | 7 | 5 | 1 |
| **CDE** | 5 | 3 | - | 1 | 0 | 2 | 0 | 1 | 1 | 0 | 8 | 3 | 4 |
| **DT** | 7 | 5 | 1 | - | 5 | 0 | 0 | 0 | 3 | 2 | 4 | 4 | 0 |
| **IoT** | 3 | 0 | 0 | 5 | - | 2 | 0 | 0 | 2 | 1 | 4 | 1 | 0 |
| **CC** | 1 | 1 | 2 | 0 | 2 | - | 0 | 1 | 4 | 1 | 6 | 1 | 0 |
| **EC** | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 |
| **5G** | 2 | 0 | 1 | 0 | 0 | 1 | 0 | - | 0 | 0 | 4 | 0 | 1 |
| **AI** | 3 | 0 | 1 | 3 | 2 | 4 | 0 | 0 | - | 3 | 3 | 1 | 1 |
| **ML** | 2 | 1 | 0 | 2 | 1 | 1 | 0 | 0 | 3 | - | 3 | 1 | 1 |
| **BD** | 5 | 7 | 8 | 4 | 4 | 6 | 0 | 4 | 3 | 3 | - | 16 | 5 |
| **AA** | 6 | 5 | 3 | 4 | 1 | 1 | 0 | 0 | 1 | 1 | 16 | - | 1 |
| **BC** | 2 | 1 | 4 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 5 | 1 | - |

**Figure 8.** Co-occurrence matrix of enabling technologies.

As expected from observed trends, Building Information Modelling (BIM) confirms its role as the most frequently associated technology, appearing in 52 articles and showing notable co-occurrence with the following:

- Digital Twin (DT): 7 occurrences;
- Geographic Information Systems (GIS): 6 occurrences;
- Common Data Environment (CDE): 5 occurrences;
- Big Data (BD): 5 occurrences;
- Advanced Analytics (AA): 6 occurrences.

The association between BIM and DT, especially, reflects the growing convergence between information modelling and dynamic simulation, which supports the development of Digital Twins for the built environment. Similarly, the co-occurrence with GIS and CDE highlights the interest in integrated approaches aimed at territorial management and the structured sharing of data.

Analytical technologies such as BD and AA demonstrate significant overlap with multiple other technologies, reinforcing their transversal role in extracting value from data generated throughout the building lifecycle.

By contrast, technologies such as Edge Computing (EC) and 5G show either no or very limited co-occurrence, confirming their current low level of maturity within the AEC sector. The limited presence of combinations involving EC suggests that distributed data processing close to the data source remains largely unadopted in current construction workflows.

### *3.2. Distribution of Enabling Technology Combinations Across Construction Process Phases: Analysis of Clusters and Emerging Trends*

Figure 9 illustrates the distribution of the main combinations of enabling technologies (e.g., BIM, AI, IoT, Digital Twin) across the four phases of the construction process: Programming, Design, Execution, and Facility Management. Quantitative data, represented through a series of bar charts for each phase, reveal an uneven adoption of technologies, with a greater concentration during the Programming (126 occurrences) and Facility Management (120) phases, compared to the Design (112) and Execution (47) phases.


**Figure 9.** Distribution of enabling technology combinations across the phases of the construction process.

During the Programming phase, combinations based on Advanced Analytics (AA) and Big Data (BD), integrated with Digital Twin (DT), Geographic Information Systems (GIS), and Machine Learning (ML), are predominant. These are employed to support strategic planning and predictive modelling. The Design phase, although characterised by a lower technological density, exhibits a gradual digital maturation through combinations such as AA + BD, AA + DT, AA + BIM, and AA + Common Data Environment (CDE), indicating a consolidation of information flows and growing interoperability.

Execution emerges as the least digitised phase. The identified combinations (e.g., 5G, BD, BIM) tend to be simple and are primarily oriented towards traceability, real-time communication, and construction site logistics. The critical issues observed in this phase are largely attributable to operational constraints, lack of standardisation, and cultural barriers.

Facility Management stands out for its technological complexity and intensity, with frequent configurations such as DT + GIS + IoT + ML and BIM + DT + IoT. These support predictive maintenance, environmental monitoring, and data-driven asset management. The Digital Twin, in particular, emerges as a key technology for adaptive asset management, aligning with the Smart Building and Smart City paradigms.

From a strategic perspective, the concentration of advanced combinations in Programming and Facility Management reflects two complementary axes: ex ante planning and ex post management. Although the intermediate phases remain less developed, they exhibit signs of growth and increasing integration.

The analysis reveals the emergence of coherent clusters:

- AA + BD (+ GIS/ML): dominant in Programming, supporting predictive analytics;
- BIM + DT + IoT: consolidated in Facility Management, for monitoring and maintenance;
- AI + BIM + IoT/ML: applied in Facility Management, for automated optimisation;
- BD + Cloud Computing (CC) + CDE: identified in both Facility Management and Execution, for document management and traceability;
- Blockchain (BC) + BD + CDE + GIS: observed in Design, facilitating interoperability.

Certain technologies play a cross-cutting role:

- AA and BD are central in the initial phase;
- BIM confirms its role as a bridging technology between design and management;
- DT is increasingly consolidated in Facility Management;
- ML appears in more advanced configurations.

Digital maturity remains uneven, with the initial and final phases being more advanced, while the Execution phase suffers from significant delays. Bridging this gap requires a more uniform diffusion of established technologies (e.g., GIS, IoT, DT) to ensure information continuity and fully realise the Digital Twin paradigm throughout the entire asset lifecycle.

### *3.3. Enabling Technology Combinations for Digitalisation: Trends, Clusters and Strategic Implications*

Figure 10 illustrates the distribution of the main combinations of enabling technologies (e.g., BIM, AI, IoT, Digital Twin) with respect to the strategic objectives of digitalisation: automation, collaboration, streamlining, risk and cost management, and transparency and traceability. The reported values indicate the frequency of each combination per objective, highlighting the presence of recurrent clusters and heterogeneous adoption patterns. This analysis enables the identification of prevailing trends, established application areas, and still marginal domains.

The resulting landscape is polarised: efficiency improvement (126 occurrences) and risk and cost management (113) emerge as the primary drivers, whereas automation (86), transparency and traceability (74), and notably collaboration (55) show lower diffusion. Thus, digitalisation appears to be oriented towards optimisation and control logics rather than participatory models.

From a technological standpoint, Big Data (BD), often combined with Advanced Analytics (AA) and Digital Twin (DT), dominates objectives related to optimisation and risk. Geographic Information Systems (GIS) correlate strongly with transparency and governance goals. Combinations such as AA + BD and AA + BD + Common Data Environment (CDE) act as versatile digital hubs, capable of addressing multiple objectives simultaneously.


**Figure 10.** Distribution of enabling technology combinations in relation to the objectives of digitalisation.

The emergence of well-defined clusters delineates three distinct approaches:

- **Analytical-decisional cluster** (AA + BD + DT, frequently with Machine Learning (ML)), focused on simulation and adaptive risk management;
- **Infrastructural-spatial cluster** (DT + GIS + IoT), prevalent in urban contexts for transparency and governance;

- **Informational-integrated cluster** (BIM + CDE + DT + GIS), aimed at semantic interoperability and document management within AEC environments.

The objective of "Collaboration" is consistently under-represented, even in the presence of collaborative technologies such as BIM, CDE, or Cloud Computing, indicating a technocratic imbalance at the expense of socio-organisational components.

From a scientific perspective, there is a clear need for digital models oriented towards multi-stakeholder participation, semantic interoperability among analytical (AA), spatial (GIS), and informational (BIM, CDE) tools, as well as metrics capable of assessing organisational and social impacts of digital transformation.

On the applied front, AA-centric configurations prove most versatile: AA + BD dominates four out of five objectives, while combinations such as AA + BIM and AA + DT integrate prediction and information modelling. AA + GIS supports territorial transparency. The 5G + BD combination also demonstrates potential in automation, albeit with limitations linked to visualisation and information control.

Strong correlations between objectives and technologies are observed:

- **Automation:** AA, BD, IoT, and 5G, for edge-to-cloud processes;
- **Collaboration:** BIM, CDE, and Cloud, for interoperability;
- **Streamlining:** AA + BD, DT + BIM, GIS, and IoT;
- **Risk and cost management:** AA + BD, GIS + BD;
- **Transparency and traceability:** GIS, CDE, Blockchain.

Emerging clusters such as AA + BD (analytical engine), BIM + DT + IoT (Facility Management), and Blockchain (BC) + BD + CDE + GIS (transparency) outline advanced scenarios, while configurations involving AI + ML + IoT anticipate Smart City and Industry 5.0 visions. Certain technologies, like AA + BD, stand out for their transversal coverage, while BIM, DT, and GIS remain central for modelling, management, and traceability. IoT and ML, though less frequent, appear in high-innovation intensity configurations.

Overall, the digital ecosystem remains imbalanced: high technological density characterises optimisation and control objectives, whereas collaborative tools are scarcely adopted. Multi-objective configurations remain rare and demand high technical and organisational maturity. To support the full spectrum of digitalisation goals, it is essential to promote integrated solutions capable of combining analytical, informational, and participatory technologies.

## 4. Enabling Technologies in the Public Administration: The Italian Case

Integrating technological innovation to achieve sustainability criteria constitutes a key objective for major governmental systems [170]. The European Union actively promotes the Twin Transition, an integrated process combining digital transition and green transition, aimed at transforming the economy and quality of life in a sustainable and innovative manner [171].

Digitalisation in the public administration sector is driven by the impetus of the European Union, where the Twin Transition is realised through the adoption and integration of digital tools and methods within public processes [172]. More specifically, modelling and information management methods such as Building Information Modelling (BIM) represent one of the enabling technologies for designing, constructing, and managing infrastructure that is more efficient, sustainable, and transparent [173]. Indeed, BIM has been promoted by the European Union since 2014 to ensure its implementation within public administration processes [174]. Consequently, several European countries are progressively adopting the European directives through their respective national government strategies [175].

After the classification matrix to the scientific context of digitalisation in the construction sector, it was considered strategic to extend the same approach to the organisational domain of public administration.

Specifically, from the analysis of the geographical distribution of the reviewed articles, Italy emerges as the country with the highest total number of publications and ranks first regarding articles related to the thematic area of BIM. Indeed, the Italian Public Procurement Code stipulates that, starting from 2025, public administrations must employ modelling and information management systems for the design and construction of new public works and existing assets in contracts exceeding EUR 2 million [6,176].

Accordingly, the Italian government has mandated a progressive integration of BIM within public administration processes through Ministerial Decree No. 560/2017, subsequently updated by Ministerial Decree No. 312/2021, which outlines the implementation timelines [177,178]. In Italy, to prevent public administrations lacking prior experience from approaching the BIM methodology unprepared, they are required to draft an organisational document in advance (Organisational Act). This document must provide a structured and organised framework to guide the integration of information management and building modelling methods within public administration processes.

The Italian context is therefore considered a case study to explore how the enabling technologies identified in the academic domain are implemented in the public sector, particularly within the Organisational Act document. Although Italian administrations are gradually introducing their own Organisational Acts, the one from the Emilia-Romagna region is the subject of analysis, as it represents the first comprehensive public document in its extended version [179]. It is important to highlight that the Emilia-Romagna Region represents a particularly relevant example within the Italian Public Administration context. Specifically, it is the first regional public administration in Italy to make its full organisational act publicly available, consisting of over 600 pages. This level of transparency and completeness is uncommon among Italian public administrations, many of which are still in the process of adopting their organisational acts or have only partially published them, for instance, providing only the index. The comprehensive availability of the Emilia-Romagna organisational act allows for a detailed and systematic examination of how digitalisation strategies, procedures, and responsibilities are formally integrated at an institutional level. Moreover, the author of the Emilia-Romagna organisational act is Harpaceas, a consultancy that is currently contributing to the drafting of organisational acts for other Italian regions and municipalities. This further reinforces the representativeness of this case and its relevance as a benchmark within the national context. Consequently, the case study provides a robust and replicable framework to analyse the alignment between academic research on digital tools in construction and their practical implementation in the public sector, offering insights that would be less accessible in administrations with limited or incomplete documentation [179].

Specifically, the analysis of the Organisational Act of the Emilia-Romagna Region provided an opportunity to assess the effectiveness of the instrument within a real and institutional context, characterised by a complex articulation of processes, stakeholders, and technologies. Indeed, the Organisational Act of Emilia-Romagna is an extensive document of 618 pages, which includes guidelines for the acquisition and maintenance of hardware and software tools supporting the implementation of various technological domains.

As expected, the technological domains considered in this act comply with the regulatory obligations of the Italian normative framework. The primary objective of the Act is to address the introduction of BIM within public administration processes and the adoption of an organisation-specific Common Data Environment (CDE).

The analysis of Figure 11 highlights the categories of enabling technologies included in the Emilia-Romagna Organisational Act, as well as the explicitly considered combinations thereof. BIM remains the core of the digital system, articulated into its four components: Authoring (AUT), Coordination (CO), Data Structure Management (DSM), and BIM Dimensions (DIM), namely 4D, 5D, and 6D extensions.

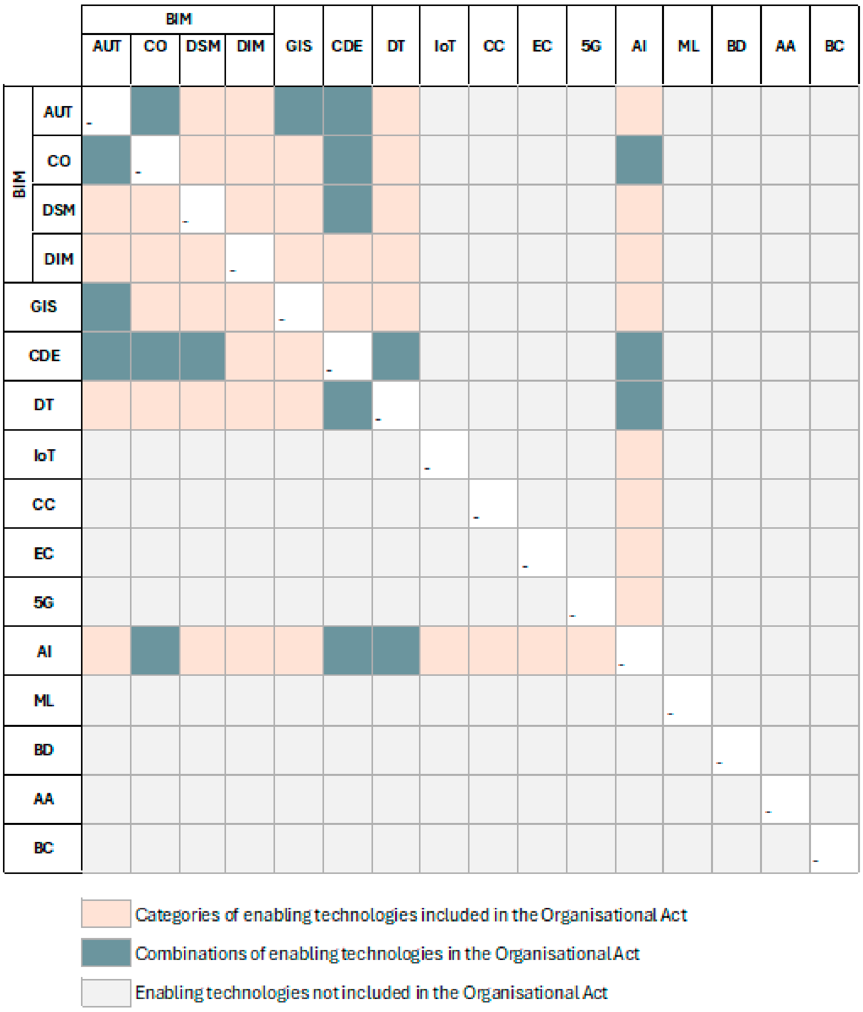


**Figure 11.** Enabling technologies combination analysis from the Emilia-Romagna Organisational Act.

These components are closely linked, within the Act, to enabling technologies such as GIS, CDE, and Digital Twin (DT), indicating a synergistic and interoperable approach to the management of design and infrastructure data.

For example, the planning of an interoperable information infrastructure based on the CDE aligns clearly with best practices described in the international literature, where the CDE is regarded as an enabling condition for effective BIM implementation and transparent data sharing between public and private actors.

Within the Organisational Act, Artificial Intelligence (AI) is recognised as an enabling technology; however, its use remains limited and predominantly described in a prospective manner. Its inclusion signals a strategic intent to embrace innovation, albeit in the absence of consolidated operational applications.

The analysis of technology combinations demonstrates that the integration of digital tools is crucial for effectively addressing the needs of public administrations (Figures 12 and 13). Among the pairs, the combination of Authoring (AUT) and Common Data Environment (CDE) stands out as the most comprehensive and crosscutting: it spans all phases of the construction process and supports key objectives such as automation, transparency, and collaboration. The CDE + Coordination (CO) pair is also particularly significant, especially during the execution phase, where coordination among stakeholders and structured data sharing play an essential role in risk management.

| **Enabling Technologies** Combinations of Two | Phase | | | |
|---|---|---|---|---|
| | Programming | Design | Execution | Facility Management |
| AUT + CDE | | ✓ | ✓ | ✓ |
| AUT + CO | | ✓ | ✓ | ✓ |
| CDE + CO | | ✓ | ✓ | |
| CDE + DSM | ✓ | ✓ | | |
| CDE + DT | ✓ | ✓ | | |
| AI + CO | | ✓ | ✓ | |
| AUT + GIS | | ✓ | ✓ | |

| **Enabling Technologies** Combinations of Three | Phase | | | |
|---|---|---|---|---|
| | Programming | Design | Execution | Facility Management |
| AUT + CDE +CO | | ✓ | ✓ | ✓ |
| CDE+DSM+GIS | ✓ | ✓ | | |
| AUT+CO+AI | | ✓ | | |

**Figure 12.** Matrix of enabling technologies related to the phases.

| **Enabling Technologies** Combinations of Two | Digitalisation scope | | | | |
|---|---|---|---|---|---|
| | Automation | Collaboration | Streamlining | Risk and cost management | Transparency and traceability |
| AUT + CDE | | ✓ | | | ✓ |
| AUT + CO | ✓ | | | ✓ | |
| CDE + CO | | | ✓ | | ✓ |
| CDE + DSM | | ✓ | ✓ | | |
| CDE + DT | | ✓ | | ✓ | |
| AI + CO | ✓ | | | | |
| AUT + GIS | | | | | ✓ |

| **Enabling Technologies** Combinations of Three | Digitalisation scope | | | | |
|---|---|---|---|---|---|
| | Automation | Collaboration | Streamlining | Risk and cost management | Transparency and traceability |
| AUT + CDE +CO | ✓ | ✓ | | | ✓ |
| CDE+DSM+GIS | ✓ | | ✓ | | ✓ |
| AUT+CO+AI | ✓ | | ✓ | ✓ | ✓ |

**Figure 13.** Matrix of enabling technologies related to the scope of the digitalisation.

Other pairs, such as CDE + Data Structure Management (DSM) or CDE + Digital Twin (DT), although more limited in scope, show a clear orientation towards the long-term management of assets, particularly in the facility management phase, confirming the growing interest in data-driven solutions and Digital Twin technologies. The pairs AUT + Geographic Information System (GIS) and Artificial Intelligence (AI) + CO introduce interesting potential, especially for programming and management, but remain relatively underdeveloped.

Triplets (Figure 13), on the other hand, display greater application maturity. The AUT + CDE + CO combination emerges as one of the most robust, covering the entire construction lifecycle and integrating objectives of efficiency, traceability, and collaboration. The CDE + DSM + GIS triplet highlights a territorial and management-oriented approach, while AUT + CO + AI introduces elements of predictive intelligence and optimisation, opening up early-stage evolutionary scenarios.

Overall, the analysed technological combinations are primarily concentrated in the design phase, followed by the execution phase, indicating that the adoption of digital technologies in public administration is prioritised during the initial operational stages of the construction lifecycle.

## 5. Discussion

The analysis confirms the emergence of a progressive digital transformation in the public construction sector, driven by a growing interest in advanced tools such as Building Information Modelling (BIM), Digital Twins (DT), the Internet of Things (IoT), and document management platforms. These enabling technologies are primarily applied during the design and facility management phases, demonstrating increasing maturity in supporting the planning, maintenance, and monitoring of structures and building objects. However, the digitalisation process remains fragmented, influenced by divergent organisational models, regulatory heterogeneity, and territorial disparities.

The results reveal a complex yet still polarised technological landscape, in which a few enabling technologies—particularly BIM, Big Data, and Advanced Analytics—dominate the scene and act as foundational pillars of digitalisation in the construction sector. The most recurring combinations are geared towards efficiency improvement, risk management, and information modelling, whereas domains such as collaboration and distributed automation remain less developed. Technological adoption is uneven across the asset lifecycle, with a strong concentration of digital solutions in the Facility Management phase and a significant lag during the execution phase.

In this context, the near absence of Edge Computing and the limited presence of technologies such as 5G, Machine Learning (ML), and Blockchain point to a structural gap in relation to the potential offered by emerging paradigms. Edge Computing, due to its ability to enable processing near the data source and provide real-time responses, is identified as a key element for overcoming current limitations—particularly in operational phases and in high-information-dynamic environments such as construction sites or complex facilities. The introduction of this technology would therefore represent a strategic direction to foster a more pervasive, responsive, and scalable digital transformation. Edge Computing, in fact, represents an emerging paradigm within digital transformation, based on data processing performed in close proximity to the point of generation. This approach should significantly reduce latency, decrease the load on central data centres, and enhance the operational autonomy of systems. The technology has found application across several data-intensive sectors, including advanced manufacturing (Industry 4.0) [180], critical infrastructure (e.g., smart grids) [181], autonomous mobility [182], and digital healthcare [183]. However, within the AEC (Architecture, Engineering, and Construction) sector, its adoption remains limited.

In the construction context, technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), and Digital Twins have reached a significantly higher level of maturity, having already been widely integrated into information flows and operational processes [28,184].

At the methodological level, the construction of a thematic matrix has enabled the identification of relationships between technologies, phases of the construction process, and strategic objectives.

The most frequent combinations, such as AA + BD, BIM + CDE, and DT + GIS + IoT, are predominantly concentrated on predictive management and operational optimisation, whereas configurations oriented towards multi-actor collaboration are rarer and remain weakly structured. This highlights a digital paradigm still centred on optimisation and automation, with limited engagement in organisational, relational, and participatory aspects.

In conclusion, our comparative analysis between the matrix and the case of the Emilia-Romagna public administration has proved useful for two main reasons: first, to compare the logics of technology adoption and integration between the scientific and operational domains; second, to offer public administrations a replicable and structured model capable of guiding technological and organisational choices in alignment with digital transformation objectives. The analysis of the regional matrix thus allows the principles observed in the literature to be translated into practice and enhanced within a public governance perspective.

The application of our structured matrix to the case of the Organisational Act enables the complexity of the regional technological ecosystem to be transformed into a synthetic and consultable decision-making repertoire, primarily addressed to public administrations. Through a coherent classification of the technologies adopted, services activated, and organisational capabilities involved, the matrix provides an integrated overview of digital choices made, making explicit the relationships between implemented tools and institutional objectives.

This approach enables public decision-makers to orient their digital strategies based on systematised evidence, supporting the monitoring of objectives, the identification of technological or organisational gaps, and the comparative evaluation across units or entities. Moreover, the matrix may facilitate the adoption of best practices, promote the standardisation of organisational models, and contribute to the development of a digital infrastructure more consistent with national and European directives. In this sense, it constitutes a strategic tool for informed governance and for digital planning grounded in structured and transparent data.

## 6. Limitations

In this paper, only articles indexed in the Scopus database and published in Open Access were considered. While this ensures accessibility and transparency in the methodological approach, it constitutes a significant limitation that may have introduced selection bias, potentially excluding high-quality studies available in other bibliographic databases (e.g., Web of Science, ProQuest) or in non-open access journals.

Moreover, the exclusion of grey literature—such as government reports, policy documents, and technical publications—may have limited the representation of institutional perspectives and real-world implementation practices, especially in the public sector.

The time period selected (2014–2024), chosen with the aim of capturing developments and innovations in the field of digitalisation, may have overlooked relevant earlier contributions.

Furthermore, as already stated in Section 2, no formal critical appraisal of the included articles was conducted, as this is not mandatory in scoping reviews.

An additional limitation concerns the language of the included studies. Only publications in English and Italian were considered. While this may have excluded relevant contributions in other languages, the decision was made to ensure both a broad international perspective (through the English-language literature) and a focused national lens (through Italian sources), in line with the scope of the Italian case study. This dual approach supports a more balanced understanding of global trends and local implementation dynamics.

Despite these limitations, the structured methodology adopted and the wide scope of the literature considered ensure that the review provides a comprehensive and representative overview of the current state of digitalisation in public administration and the construction sector.

## 7. Conclusions

In line with the objectives of the Twin Transition promoted by the European Union, our contribution aims to offer a critical and forward-looking framework for the digital and sustainable transformation of Public Administrations in the domain of public works.

Especially, the analysis focuses on the structured integration of information management methods and digital modelling—such as Building Information Modelling (BIM) and

Digital Twin—throughout the entire lifecycle of public procurement, as outlined by the Italian Public Procurement Code (Legislative Decree No. 36/2023).

The investigation adopts a two-tiered methodological approach:

A knowledge-oriented review, carried out through a systematic analysis of the scientific literature published between 2014 and 2024, aimed at reconstructing the evolution, application trajectories, and dissemination of digital technologies in the construction sector.

An applied inquiry, based on the analysis of regional organisational acts and the development of a classification matrix designed to provide an integrated view of the technologies employed, the organisational capabilities activated, and the strategic objectives pursued.

The analysis conducted by our research group, both on scientific literature and on the case study of the Emilia-Romagna Region, highlights a series of structural gaps that hinder the effective adoption of digital technologies within the operational processes of public administrations, despite growing interest in solutions such as BIM, Digital Twin, Artificial Intelligence, and the Internet of Things. Specifically, five key critical issues have been identified:

- The lack of operational tools supporting the systematic integration of digital technologies across public procurement phases;
- The limited standardisation of digital decision-making processes, which remain fragmented and dependent on heterogeneous local practices;
- The absence of support models grounded in structured evidence and up-to-date regulatory references (e.g., Legislative Decree No. 36/2023);
- The discontinuity between the theoretical-methodological dimension (scientific literature) and organisational implementation (regional acts, internal procedures);
- The difficulty in aligning strategic digitalisation objectives with specific technologies and applicable solutions.

Unlike previous reviews, this study not only maps the adoption of digital technologies in construction but also explicitly compares academic discussions with the strategies and practices implemented by PAs, considering at the same time procedures, processes, and protocols. The introduction of a thematic classification matrix, combined with the analysis of the Emilia-Romagna case study, provides a novel framework for assessing convergence between research and practice in the digitalisation of public construction processes.

In light of these findings, future developments could include the design of a digital decision-support platform to assist Public Administration in identifying the most appropriate technological combinations, based on strategic goals, the relevant phases of the construction process, and the specific operational context.

Such a platform could represent a strategic lever for the modernisation of public governance, with the potential to:

- Promote informed and guided adoption of digital technologies;
- Foster standardisation of decision-making and operational models;
- Strengthen the technical and organisational capacities of public bodies;
- Contribute to the development of a robust, interoperable public digital infrastructure aligned with national and European directives.

From a policy perspective, the results underline the urgency of reinforcing regulatory coordination and investing in continuous training to enhance digital maturity across Public Administrations. For practice, the proposed framework can support decision-makers and professionals in selecting effective technological solutions, ensuring interoperability, and reducing fragmentation.

This perspective also opens promising avenues for further research and development, both in terms of the scalability of the proposed infrastructure to other application domains (e.g., healthcare, infrastructure, cultural heritage), and in relation to its integration with real-time monitoring systems, predictive models, and artificial intelligence tools, oriented towards a more proactive, transparent, and efficient management of the public works lifecycle.

Future research should also prioritise cross-national comparative studies, the development of shared impact metrics (such as efficiency, cost reduction, and sustainability), and the exploration of organisational, social, and cultural aspects of digital transformation, including stakeholder collaboration and change management.

**Author Contributions:** Conceptualisation, G.D., K.R., V.A.T. and U.M.C.; methodology, G.D., K.R., V.A.T. and U.M.C.; validation, U.M.C.; data curation, G.D., K.R., V.A.T. and U.M.C.; writing—original draft preparation, G.D., K.R., V.A.T. and U.M.C.; writing—review and editing, G.D., K.R., V.A.T. and U.M.C.; supervision, U.M.C. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| PA | Public Administration |
| BIM | Building Information Modelling |
| DT | Digital Twin |
| NIST | National Institute of Standards and Technology |
| AI | Artificial Intelligence |
| ISO | International Organization for Standardization |
| UNI | Italian National Standards Body |
| ID | Article Identifier |
| IR | Integration |
| IC | Intelligence |
| UX | User Experience |
| MN | Management |
| TW | Trustworthiness |
| IT | Innovation technology |
| PROC | Processes |
| PROT | Protocols |
| DP | Digital Process |
| GIS | Geographic Information System |
| QGIS | Quantum Geographic Information System |
| CDE | Common Data Environment |
| ACDat | Ambiente di Condivisione Dati (Italian CDE) |
| ACC | Autodesk Construction Cloud |
| IFC | Industry Foundation Classes |
| VEWS | Ventilation Early Warning System |
| BLE | Bluetooth Low Energy |
| CC | Cloud Computing |
| EC | Edge Computing |
| ML | Machine Learning |
| BD | Big Data |
| KPI | Key Performance Indicator |
| AA | Advanced Analytics |
| SBM | Soft Building Modelling |
| DS | Data Services |
| BC | Blockchain |

| | |
|---|---|
| FM | Facility Management |
| AEC | Architecture, Engineering, and Construction |
| AUT | Automation |
| CO | Collaboration |
| DIM | Dimension BIM |

## Appendix A

**Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist**

| SECTION | ITEM | PRISMA-ScR CHECKLIST ITEM | REPORTED ON PAGE # |
|---|---|---|---|
| **TITLE** | | | |
| Title | 1 | Identify the report as a scoping review. | 1 |
| **ABSTRACT** | | | |
| Structured summary | 2 | Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives. | 1 |
| **INTRODUCTION** | | | |
| Rationale | 3 | Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach. | 2–4 |
| Objectives | 4 | Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives. | 4–5 |
| **METHODS** | | | |
| Protocol and registration | 5 | Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number. | 5 |
| Eligibility criteria | 6 | Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale. | 7–9 |
| Information sources* | 7 | Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed. | 7–8 |
| Search | 8 | Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated. | 6–7 |
| Selection of sources of evidence† | 9 | State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review. | 6–7, 11–12 |
| Data charting process‡ | 10 | Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators. | 9–10 |
| Data items | 11 | List and define all variables for which data were sought and any assumptions and simplifications made. | 9–10 |
| Critical appraisal of individual sources of evidence§ | 12 | If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate). | 5 |
| Synthesis of results | 13 | Describe the methods of handling and summarizing the data that were charted. | 10 |

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**Figure A1.** *Cont.*

| SECTION | ITEM | PRISMA-ScR CHECKLIST ITEM | REPORTED ON PAGE # |
|---|---|---|---|
| **RESULTS** | | | |
| Selection of sources of evidence | 14 | Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram. | 11–12 |
| Characteristics of sources of evidence | 15 | For each source of evidence, present characteristics for which data were charted and provide the citations. | 14–15; App. A Figures A2–A3 |
| Critical appraisal within sources of evidence | 16 | If done, present data on critical appraisal of included sources of evidence (see item 12). | Not applicable |
| Results of individual sources of evidence | 17 | For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives. | 15; Appendix A Fig. A3 |
| Synthesis of results | 18 | Summarize and/or present the charting results as they relate to the review questions and objectives. | 15–25 |
| **DISCUSSION** | | | |
| Summary of evidence | 19 | Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups. | 28–30 |
| Limitations | 20 | Discuss the limitations of the scoping review process. | 30 |
| Conclusions | 21 | Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps. | 30–31 |
| **FUNDING** | | | |
| Funding | 22 | Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review. | 31 |

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

*From:* Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

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2

**Figure A1.** PRISMA-ScR-Checklist [24].

| List_n# | Autors | Title | Year |
|---|---|---|---|
| BIM001 | Matos B.C.; et al. | Digitalization And Procurement In Construction Projects: An Integrated Bim-Based Approach | 2024 |
| BIM002 | Raitviir C.-R. & Lill I. | Conceptual Framework of Information Flow Synchronization Throughout the Building Lifecycle | 2024 |
| BIM003 | Jeong D.; et al. | Building Digital Twin Data Model Based on Public Data | 2024 |
| BIM004 | Mutani G.; et al. | Urban Building Energy Modeling to Support Climate-Sensitive Planning in the Suburban Areas of Santiago de Chile | 2024 |
| BIM005 | Aragón A. & Alberti M.G. | Limitations of machine-interpretability of digital EPDs used for a BIM-based sustainability assessment of construction assets | 2024 |
| BIM006 | Tuscher M.; et al. | Usage of Building Passports and BIM in Multi-Criteria Evaluation | 2024 |
| BIM007 | Fonseca Arenas N. & Shafique M. | Recent progress on BIM-based sustainable buildings: State of the art review | 2023 |
| BIM008 | Colucci E.; et al. | The development of a 2d/3d bim-gis web platform for planned maintenance of built and cultural heritage: The main10ance project | 2023 |
| BIM009 | Murguia D.; et al. | The role of the industry's cultural-cognitive elements on actors' intention to adopt BIM: an empirical study in Peru | 2023 |
| BIM010 | Youkhanna Zaia Y.; et al. | Investigating BIM level in Iraqi construction industry | 2023 |
| BIM011 | Congiu E.; et al. | Web-Based Management of Public Buildings: A Workflow Based on Integration of BIM and IoT Sensors with a Web–GIS Portal | 2023 |
| BIM012 | Farghaly K.; et al. | CONSTRUCTION SAFETY ONTOLOGY DEVELOPMENT AND ALIGNMENT WITH INDUSTRY FOUNDATION CLASSES (IFC) | 2022 |
| BIM013 | Zheng H.; et al. | Evacuation in Buildings Based on BIM: Taking a Fire in a University Library as an Example | 2022 |
| BIM014 | Göswein V.; et al. | Circular material passports for buildings - Providing a robust methodology for promoting circular buildings | 2022 |
| BIM015 | Awwad K.A.; et al. | Exploring the critical success factors influencing BIM level 2 implementation in the UK construction industry: the case of SMEs | 2022 |
| BIM016 | Diana L.; et al. | Assessment of Disused Public Buildings: Strategies and Tools for Reuse of Healthcare Structures | 2022 |
| BIM017 | Andrich W.; et al. | Check and Validation of Building Information Models in Detailed Design Phase: A Check Flow to Pave the Way for BIM Based Renovation and Construction Processes | 2022 |
| BIM018 | Othman I.; et al. | The level of Building Information Modelling (BIM) Implementation in Malaysia | 2021 |
| BIM019 | Belay S.; et al. | Enhancing BIM implementation in the Ethiopian public construction sector: An empirical study | 2021 |
| BIM020 | Rey-Merchán M.C.; et al. | Virtual fence system based on IoT paradigm to prevent occupational accidents in the construction sector | 2021 |
| BIM021 | Marinho A.; et al. | Relational contracting and its combination with the bim methodology in mitigating asymmetric information problems in construction projects | 2021 |
| BIM022 | Lindblad H. & Karrbom Gustavsson T. | Public clients ability to drive industry change: the case of implementing BIM | 2021 |
| BIM023 | Nguyen T.-Q. & Nguyen D.-P. | Barriers in bim adoption and the legal considerations in Vietnam | 2021 |
| BIM024 | Alfieri E.; et al. | A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study | 2020 |
| BIM025 | Vidalakis C.; et al. | BIM adoption and implementation: focusing on SMEs | 2020 |
| BIM026 | Andújar-Montoya M.D.; et al. | BIM-LEAN as a methodology to save execution costs in building construction-An experience under the spanish framework | 2020 |
| BIM027 | van Eldik M.A.; et al. | BIM-based environmental impact assessment for infrastructure design projects | 2020 |
| BIM028 | Alvanchi A. & Seyrfar A. | Improving facility management of public hospitals in Iran using building information modeling | 2020 |
| BIM029 | Zhang L.; et al. | Investigating the constraints to buidling information modeling (BIM) applications for sustainable building projects: A case of China | 2019 |
| BIM030 | Janečka K. | Standardization supporting future smart cities- A case of BIM/GIS and 3D cadastre | 2019 |
| BIM031 | Ma G.; et al. | The evaluation of building fire emergency response capability based on the CMM | 2019 |
| BIM032 | Moreno C.; et al. | BIM Use by Architecture, Engineering, and Construction (AEC) Industry in Educational Facility Projects | 2019 |
| BIM033 | Chang Y.-T.; et al. | A Preliminary Case Study on Circular Economy in Taiwan's Construction | 2019 |
| BIM034 | Hatem W.A.; et al. | Barriers of adoption building information modeling (BIM) in construction projects of Iraq | 2018 |
| BIM035 | Galiano-Garrigós A. & Andújar-Montoya M.D. | Building information modelling in operations of maintenance at the university of alicante | 2018 |
| BIM036 | Osello A.; et al. | BIM Methodology Approach to Infrastructure Design: Case Study of Paniga Tunnel | 2017 |
| BIM037 | Love P.E.D.; et al. | Off the rails: The cost performance of infrastructure rail projects | 2017 |
| BIM038 | Sadeghifam A.N.; et al. | Energy analysis of wall materials using building information modeling (BIM) of public buildings in the tropical climate countries | 2016 |
| BIM039 | Azzi M.; et al. | Toward sustainable energy usage in the power generation and construction sectors - a case study of Australia | 2015 |
| BIM040 | Giovannini L.; et al. | Large-scale assessment and visualization of the energy performance of buildings with ecomaps: Project SUNSHINE: Smart urban services for higher energy efficiency | 2014 |
| BIM041 | Demian P. & Walters D. | The advantages of information management through building information modelling | 2014 |
| DT042 | Piras G.; et al. | Enhancing Space Management through Digital Twin: A Case Study of the Lazio Region Headquarters | 2024 |
| DT043 | Costa G.; et al. | A ventilation early warning system (VEWS) for diaphanous workspaces considering COVID-19 and future pandemics scenarios | 2023 |
| DT044 | Fialho B.C.; et al. | Development of a BIM and IoT-Based Smart Lighting Maintenance System Prototype for Universities' FM Sector | 2022 |
| DT045 | Tagliabue L.C.; et al. | Leveraging digital twin for sustainability assessment of an educational building | 2021 |
| DT046 | Steadman P.; et al. | Building stock energy modelling in the UK: the 3DStock method and the London Building Stock Model | 2020 |
| IT047 | Saputra N.; et al. | Capacity building for organizational performance: a systematic review, conceptual framework, and future research directions | 2024 |
| IT048 | Kaššaj M. & Peráček T. | Sustainable Connectivity—Integration of Mobile Roaming, WiFi4EU and Smart City Concept in the European Union | 2024 |
| IT049 | Pérez-García A.; et al. | Enhancing BIM implementation in Spanish public procurement: A framework approach | 2024 |
| IT050 | Bitkowska A.; et al. | Towards integration of business process management and knowledge management. IT systems' perspective | 2023 |
| IT051 | Wang B.; et al. | Spatiotemporal Differentiation and Influencing Factors of Green Technology Innovation Efficiency in the Construction Industry: A Case Study of Chengdu–Chongqing Urban Agglomeration | 2023 |
| IT052 | Khan S.; et al. | Blockchain for Governments: The Case of the Dubai Government | 2022 |
| IT053 | Domaradzka A.; et al. | The Civil City Framework for the Implementation of Nature-Based Smart Innovations: Right to a Healthy City Perspective | 2022 |
| IT054 | Fregonara E.; et al. | Sustainable Public Procurement in the Building Construction Sector | 2022 |
| IT055 | Yusuf A.O.; et al. | Capability improvement measures of the public sector for implementation of building information modeling in construction projects | 2022 |
| IT056 | Mahmud H. & Roy J. | Barriers to overcome in accelerating renewable energy penetration in Bangladesh | 2021 |
| IT057 | Jahanger Q.K.; et al. | Potential positive impacts of digitalization of construction-phase information management for project owners | 2021 |
| IT058 | Toivonen R.; et al. | Policy narratives on wooden multi-storey construction and implications for technology innovation system governance | 2021 |
| IT059 | He N.; et al. | Critical factors to achieve sustainability of public-private partnership projects in the water sector: A stakeholder-oriented network perspective | 2020 |
| IT060 | Hale L.A. | Business model innovation for smart, healthy buildings | 2020 |
| IT061 | Wieteska-Rosiak B. | Real estate sector in the face of climate change adaptation in major Polish cities | 2020 |
| IT062 | Mills E. | Algorithms and the near future of design | 2019 |
| IT063 | Pentsev E.A. & Makarova O.A. | Big data in urban planning and territory management | 2019 |
| IT064 | Mohamad R.; et al. | Performance indicators for public private partnership (PPP) projects in Malaysia | 2018 |
| IT065 | Gusta S.; et al. | BIM opportunities and challenges in construction study programs at Latvia university of life sciences and technologies | 2018 |
| IT066 | Barbosa A.A.R. & Vilnitis M. | Innovation and construction management in Brazil: Challenges of companies in times of quality and productivity | 2017 |
| IT067 | Lovell K. & Nightingale P. | Business models in rail infrastructure: Explaining innovation | 2016 |
| IT068 | Kern F.; et al. | Empowering sustainable niches: Comparing UK and Dutch offshore wind developments | 2015 |
| IT069 | Vernikos V.K.; et al. | Building information modelling and its effect on off-site construction in UK civil engineering | 2014 |
| DP70 | Kim S., et al. | Public Technologies Transforming Work of the Public and the Public Sector | 2024 |
| DP71 | Atobishi T., et al. | How Do Digital Capabilities Affect Organizational Performance in the Public Sector? The Mediating Role of the Organizational Agility | 2024 |
| DP72 | Durand A., et al. | Fostering an inclusive public transport system in the digital era: An interdisciplinary approach | 2023 |
| DP73 | Wik M., et al. | Modes of Engagement: Problematizing Managerial Assumptions of Participation in Public Sector Digital Transformation: Problematizing managerial assumptions of participation in public sector digital transformation | 2023 |
| DP74 | Dolla T., et al. | STRATEGIES FOR DIGITAL TRANSFORMATION IN CONSTRUCTION PROJECTS: STAKEHOLDERS' PERCEPTIONS AND ACTOR DYNAMICS FOR INDUSTRY 4.0" | 2023 |
| DP75 | Serkina Y., et al. | Digitalization processes vs. traditional ones: ethical and environmental aspects | 2022 |
| DP76 | Maki O., et al. | Development of Digitalization Road Map for Healthcare Facility Management | 2022 |
| DP77 | Raco F., et al. | TOWARDS EFFECTIVE PROJECT DOCUMENTATION, TRANSPARENCY, and DATA-DRIVEN DECISION-MAKING through BIM-BLOCKCHAIN BASED APPLICATIONS | 2021 |
| DP78 | Nosova S., et al. | Digital transformation as a new paradigm of economic policy | 2021 |
| DP79 | Di Giuda, G, et al. | A workflow for building site digitalization. | 2021 |
| DP80 | Pavan A., et al. | BIMReL: A new BIM object library using Construction Product Regulation attributes (CPR 350/11, ZA annex) | 2019 |
| DP81 | Fasoli A., et al. | Engaged by Design: The Role of Emerging Collaborative Infrastructures for Social Development. Roma Makers as A Case Study | 2017 |
| DP82 | Bataw A., et al. | The Issues and Considerations Associated with BIM Integration | 2016 |
| DP83 | Wood J., et al. | Moving beyond sequential design: Reflections on a rich multi-channel approach to data visualization | 2014 |
| PROC84 | Sethi M., et al. | How to tackle complexity in urban climate resilience? Negotiating climate science, adaptation and multi-level governance in India | 2021 |
| PROC85 | Zekić-Sušac M., et al. | Machine learning based system for managing energy efficiency of public sector as an approach towards smart cities | 2021 |
| PROC86 | Oad P.K., et al. | Investigation of innovation during bid evaluation process in the road construction industry | 2021 |
| PROC87 | Morano P., et al. | The public role for the effectiveness of the territorial enhancement initiatives: A case study on the redevelopment of a building in disuse in an Italian small town | 2021 |
| PROC88 | Serrano-Jiménez A., et al. | A multi-criteria decision support method towards selecting feasible and sustainable housing renovation strategies | 2021 |
| PROC89 | Dejaco M.C., et al. | Combining LCA and LCC in the early-design stage: A preliminary study for residential buildings technologies | 2020 |
| PROC90 | Fernandez J., et al. | A novel residential heating consumption characterisation approach at city level from available public data: Description and case study | 2020 |
| PROC91 | Fiore P., et al. | An ahp-based methodology for the evaluation and choice of integrated interventions on historic buildings | 2020 |
| PROC92 | Kim H. & Jeon E.-C. | Structural changes to nuclear energy industries and the economic effects resulting from energy transition policies in South Korea | 2020 |
| PROC93 | Bakogiannis E., et al. | How to adopt BIM in the building construction sector across greece? | 2020 |
| PROC94 | Plachkova T. & Avdieiev O. | Public administration of safety of navigation: Multi-level challenges and answers | 2020 |
| PROC95 | Li C. & Xi Z. | Social stability risk assessment of land expropriation: Lessons from the Chinese case | 2019 |
| PROC96 | Manikam S., et al. | Business intelligence addressing service quality for big data analytics in public sector | 2019 |
| PROC97 | Fuentes-Bargues J.L., et al. | Green public procurement at a regional level. Case study: The valencia region of Spain | 2019 |
| PROC98 | Erlandson G., et al. | Characterization of indoor air quality on a college campus: A pilot study | 2019 |
| PROC99 | Weng X.-H., et al. | Identification of key success factors for private science parks established from brownfield regeneration: A case study from China | 2019 |
| PROC100 | Khakh A.K., et al. | Spatial accessibility to primary healthcare services by multimodal means of travel: Synthesis and case study in the city of calgary | 2019 |
| PROC101 | Volden G.H. | Public project success as seen in a broad perspective.: Lessons from a meta-evaluation of 20 infrastructure projects in Norway | 2018 |
| PROC102 | Thomann E. & Rapp C. | Who Deserves Solidarity? Unequal Treatment of Immigrants in Swiss Welfare Policy Delivery | 2018 |
| PROC103 | Marrone P., et al. | Energy benchmarking in educational buildings through cluster analysis of energy retrofitting | 2018 |
| PROC104 | Novembri G., et al. | Improving the integration between bims and agent-based simulations: The swarm building modeling – sbm | 2018 |
| PROC105 | Fuentes-Bargues J.L., et al. | Environmental criteria in the spanish public works procurement process | 2017 |
| PROC106 | Macek D. & Snížek V. | Innovation in Bridge Life-cycle Cost Assessment | 2017 |
| PROC107 | Rynska E., et al. | Sustainable interdisciplinary transformation of warsaw university of technology buildings. Kodnzeb case study | 2017 |
| PROC108 | Amponsah-Tawaih K. & Adu M.A., | Work Pressure and Safety Behaviors among Health Workers in Ghana: The Moderating Role of Management Commitment to Safety | 2016 |
| PROC109 | Laña I., et al. | The role of local urban traffic and meteorological conditions in air pollution: A data-based case study in Madrid, Spain | 2016 |
| PROC110 | Shiel C., et al. | Evaluating the engagement of universities in capacity building for sustainable development in local communities | 2016 |
| PROC111 | Choi J. & Kim I., | Development of an open BIM-based legality system for building administration permission services | 2015 |
| PROC112 | Glumac B., et al. | Negotiation issues in forming public-private partnerships for brownfield redevelopment: Applying a game theoretical experiment | 2016 |
| PROC113 | Hanák T. & Muchová P. | Impact of Competition on Prices in Public Sector Procurement | 2015 |
| PROC114 | Arsovski S., et al. | Advantages of using an ontological model of the state development funds | 2014 |
| PROC115 | Grazini C. | Energy poverty as capacity deprivation: A study of social housing using the partially ordered set | 2024 |
| PROC116 | Ismaeil E.M.H. & Sobaih A.E.E. | A Proposed Model for Variation Order Management in Construction Projects | 2024 |
| PROC117 | Husin A.E., et al. | Blockchain-BIM: reducing cost in green retrofitting for sustainable construction development | 2024 |
| PROC118 | Arsenos P. & Giannadakis G., | Construction Projects' Waste Prevention and Expected Minimization of Cost and Environmental Impacts through Adopting a Comprehensive System for Document Management | 2023 |
| PROC119 | Bartonek D., et al. | Case Study of Remodelling the As-Built Documentation of a Railway Construction into the BIM and GIS Environment | 2023 |
| PROC120 | Ramos M., et al. | Strategies to promote construction and demolition waste management in the context of local dynamics | 2023 |
| PROC121 | Al-Raqeb H., et al. | Understanding the challenges of construction demolition waste management towards circular construction: Kuwait Stakeholder's perspective | 2023 |
| PROC122 | Mokeeva T. & Yurko K. | Using Digital Tools in Government Procurement Analysis: Detecting Suspicious Purchases with Control Indicators | 2023 |
| PROC123 | Guler D. & Yomralioglu T. | THE ROLE OF OPEN STANDARDS IN DIGITAL BUILDING PERMITTING, 3D REGISTRATION OF CONDOMINIUM, AND UPDATE OF 3D CITY MODELS | 2022 |
| PROC124 | Kim K.-H., et al. | Information and communication technology-based service platform enabling the co-creation of agrometeorological services: A case study of the Laos Climate Services for Agriculture | 2022 |
| PROC125 | Schumacher R., et al. | Analysis of current practice and future potentials of LCA in a BIM-based design process in Germany | 2022 |
| PROC126 | Alfreahat D. & Sebestyén Z. | A construction-specific extension to a standard project risk management process | 2022 |
| PROC127 | Hamza S.A., et al. | Procurement challenges analysis of Iraqi construction projects | 2022 |
| PROT128 | Bua C., et al. | GymHydro: An Innovative Modular Small-Scale Smart Agriculture System for Hydroponic Greenhouses | 2024 |
| PROT129 | Koasidis K., et al. | Equipment- and Time-Constrained Data Acquisition Protocol for Non-Intrusive Appliance Load Monitoring | 2023 |
| PROT130 | Branco P.T.B.S.,et al. | Quantifying indoor radon levels and determinants in schools: A case study in the radon-prone area Galicia–Norte de Portugal Euroregion | 2023 |
| PROT131 | Jones K., et al. | HBM4EU Diisocyanates Study—Research Protocol for a Collaborative European Human Biological Monitoring Study on Occupational Exposure | 2022 |
| PROT132 | Itoo S., et al. | CKMIB: Construction of Key Agreement Protocol for Cloud Medical Infrastructure Using Blockchain | 2022 |
| PROT133 | Meiss A., et al. | Indoor air quality in naturally ventilated classrooms. Lessons learned from a case study in a covid-19 scenario | 2021 |
| PROT134 | Alsharef A., et al. | Early impacts of the COVID-19 pandemic on the United States construction industry | 2021 |
| PROT135 | Barbini A., et al. | Integration of life cycle data in a BIM object library to support green and digital public procurements | 2020 |
| PROT136 | Sheng M., et al. | Economic analysis of dynamic inductive power transfer roadway charging system under public-private partnership–Evidence from New Zealand | 2020 |
| PROT137 | Symanski E., et al. | Metal air pollution partnership solutions: Building an academic-government-community-industry collaboration to improve air quality and health in environmental justice communities in Houston | 2020 |
| PROT138 | Meinig C., et al. | Public private partnerships to advance regional ocean observing capabilities: A saildrone and NOAA-PMEL case study and future considerations to expand to global scale observing | 2019 |
| PROT139 | Ramalho Luz C.M.D. ,et al. | Organizational commitment, job satisfaction and their possible influences on intent to turnover | 2018 |
| PROT140 | Páez R., et al. | Regional positioning services as economic and construction activity indicators: the case study of Andalusian Positioning Network (Southern Spain) | 2017 |

**Figure A2.** List of 140 selected articles [30–169].

| ID Article | Type of case study: Infrastructure | Type of case study: Buildings | Type of case study: Urban | Approach Type: Review | Approach Type: Methodological | Approach Type: Application | Phases of the construction process: Programming | Phases of the construction process: Design | Phases of the construction process: Execution | Phases of the construction process: FM | Goals of Digitalization: Automation | Goals of Digitalization: Efficiency Improvement | Goals of Digitalization: Transparency and Traceability | Goals of Digitalization: Risk and Cost Management | Goals of Digitalization: Collaboration | Technological Capabilities: DS | IR | IC | UX | MN | TW | Enabling Technologies: BIM | GIS | CDE | DT | IoT | CC | EC | 5G | AI | ML | BD | AA | BC | Best Practice / Adopted Strategy | Critical Issue |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIM001 | | X | | | X | X | | | | X | | | | | | | | | | | | X | | | | | | | | | | | | | Integrated procurement model with BIM and guidelines | Lack of regulatory references to BIM in tender document workflows |
| BIM002 | X | | X | X | X | | X | | | X | | X | X | X | X | | | | | | | X | X | | X | | | | | | | | | | Continuous information flow with digital twin, open standards, and BIM-Geo synchronization | Fragmentation of processes and loss of information across the building lifecycle |
| BIM003 | | X | X | | X | X | X | X | | | X | | X | | | | | | | | | | X | | X | | | | | | | | | | Use of public data mapped in CityGML and modeled in UML to build a building Digital Twin model | Lack of a consistent national standard for the use of open data in the digital twin |
| BIM004 | | X | X | | X | X | X | | | | | X | X | X | | | | | | | | | X | | X | | | | | | X | X | X | | Use of UBEM and GIS for urban retrofit and energy planning in Santiago de Chile | Need for local climate strategies and economic assessments in retrofits |
| BIM005 | X | | | | X | | | X | | | | X | | | | | | | | | | X | | | | | | | | | | | | | Critical analysis of standardized formats for the transferability of EPD data into BIM for LCA | Poor interoperability and lack of unified semantics in digital EPDs |
| BIM006 | | X | | | X | | | | | X | | X | | X | | | | | | | | X | | | | | | | | | | | | | Use of Building Passports and BIM for multi-criteria assessments in facility management | Need to define thresholds and criteria for the evaluation and efficient management of buildings |
| BIM007 | | X | | X | | | X | X | | | X | X | | | | | | | | | | X | | | | | | | | | X | | | | Review on the use of BIM, BEM, and LCA for sustainable buildings | Lack of integrated tools in BIM software for sustainability |
| BIM008 | | X | X | | X | X | | | | X | | X | X | | X | | | | | | | X | X | X | X | | | | | | | | X | | Development of a BIM-GIS web platform for the scheduled maintenance of assets | Complexity in shared management and interoperability among heterogeneous systems |
| BIM009 | | X | | X | X | | | | | | | | X | | X | | | | | | | X | | | | | | | | | | | | | Empirical study on the cultural factors influencing BIM adoption in Peru | Lack of standards, incentives, and training on collaborative processes |
| BIM010 | X | | | X | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | Analysis of BIM maturity level and barriers in the AEC sector | Lack of BIM experts, low awareness, traditional methods |
| BIM011 | | X | X | | X | X | | | | X | | X | X | | | | | | | | | X | X | | X | | | | | | | | X | | Integration of BIM, IoT, and GIS for urban energy management through an open platform | Need for tools accessible also to non-expert users to enhance participation |
| BIM012 | | X | | | X | X | X | X | | | | | X | X | X | | | | | | | X | | | | | | | | | | | X | | Development of a SHE ontology integrated with IfcOWL for safety in design | Lack of interoperability in safety information |
| BIM013 | | X | | | X | X | | | | X | | X | X | X | | | | | | | | X | | | | | | | | | | | X | | Use of Revit, Pyrosim, and Pathfinder to optimize evacuation in a library | Inefficient evacuation in pre-planning; need to optimize layout and signage |
| BIM014 | | X | | X | X | | | X | | X | | X | X | | | | | | | | | X | | | | | | | | | | | | | Integration of Circular Material Passports with the EU Level(s) framework and BIM for the circular economy | Need for standardization and regulation for the widespread adoption of CMPs |
| BIM015 | | X | | X | X | X | | | | | | | | X | X | | | | | | | X | | | | | | | | | | | | | Analysis of critical factors for the adoption of BIM Level 2 in SMEs | Low adoption of BIM in SMEs due to lack of resources and training |
| BIM016 | | X | | | X | X | | X | | | | X | X | X | X | | | | | | | X | X | | | | | | | | | | | | Methodology for assessing the reuse potential of decommissioned public buildings | Structural and architectural constraints limit the transformability of buildings |
| BIM017 | | X | | | X | X | | X | | | | X | X | X | | | | | | | | X | | | | | | | | | | | | | Structured workflow for model checking in the detailed design phase | Lack of practical guidelines for BIM model validation |
| BIM018 | | X | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | Analysis of the level of BIM implementation in Malaysia | Low awareness, costs, slow adoption, lack of guidelines |
| BIM019 | X | | | X | X | | | | | | | | | | X | | | | | | | X | | | | | | | | | | | | | Empirical analysis of the benefits and barriers of BIM in the Ethiopian public sector | Poor IT infrastructure, insufficient government support, lack of training |
| BIM020 | X | | | | X | X | | X | X | | X | | | | | | | | | | | | | | | X | | | | | | | | | Development of a BLE virtual fence system for construction site safety | Adoption conditioned by costs, managerial support, and compatibility with existing systems |
| BIM021 | | X | | | X | X | | X | | | | | X | | X | | | | | | | X | | | | | | | | | | | | | Use of relational contracting combined with BIM to reduce information asymmetry | High incidence of information asymmetry in public projects in Portugal |
| BIM022 | | X | | X | X | | X | | | | | X | X | | X | | | | | | | X | | | | | | | | | | | | | Analysis of the capacity of public clients to drive change through BIM | Difficulty in translating knowledge into concrete transformations |
| BIM023 | | X | | | X | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | Analysis of legal and environmental barriers to BIM adoption in VietnamAnalysis of legal and environmental barriers to BIM adoption in Vietnam | Lack of standards, roadmap, and government incentives |
| BIM024 | | X | | | X | X | | X | | | | X | | X | | | | | | | | X | | | | | | | | | | | | | Integration of DfMA into the Italian construction process through BIM | Need for structured information flows for off-site construction |
| BIM025 | | X | | X | | X | | | | | | | | | X | | | | | | | X | | | | | | | | | | | | | Qualitative-quantitative study on the factors influencing BIM adoption in SME | Low familiarity with BIM software and limited financial capacity |
| BIM026 | | X | | | X | X | | X | X | | X | X | X | X | X | | | | | | | X | | | | | | | | | | | | | Integration of BIM and Lean Construction (Last Planner System) to reduce costs and deviations in public projects | Ineffective traditional methods, need for integrated BIM-LEAN approaches |
| BIM027 | X | | | | X | X | | X | | | | X | X | X | X | | | | | | | X | | | | | | | | | | | | | Framework for continuous environmental impact assessment through BIM | Interoperability, bidirectionality, and accessibility of the BIM-EIA data flow |
| BIM028 | | X | | X | X | X | | | | X | | X | X | | X | | | | | | | X | | | | | | | | | | | | | Use of BIM to optimize the management of public hospital services | Low adoption of BIM in hospital FM (Facility Management) |
| BIM029 | | X | | | X | X | | X | | X | | X | X | X | | | | | | | | X | | | | | | | | | | | | | Identification of the main constraints to BIM adoption in sustainable projects | Limited public participation, costs, and management issues in the application of BIM to sustainability |
| BIM030 | X | | X | X | X | | | X | | | | X | X | | X | | | | | | | X | X | | | | | | | | | | | | ISO standards for BIM-GIS and 3D cadastre for smart | Need for interoperability and standardization between BIM and GIS systems |
| BIM031 | | X | X | | X | X | | X | | X | | X | X | X | | | | | | | | X | | | | | | | | | | | | | Plug-in on BIM platform for evaluating emergency response capacity | Limited intelligence and applicability of existing assessment systems |
| BIM032 | | X | | | | X | | | | | | X | | | X | | | | | | | X | | | | | | | | | | | | | Survey on the use of BIM in educational projects in the USA | Obstacles: lack of skills and need for training |
| BIM033 | | X | | | X | X | | X | | | | X | X | | | | | | | | | X | | | | | | | | | | | | | Use of BIM to support construction projects | Poor understanding and knowledge of circular economy principles and the role of BIM |
| BIM034 | | X | | X | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | Empirical analysis of the main constraints to BIM adoption in Iraqi projects | Poor knowledge of BIM, weak government support, resistance to change |
| BIM035 | | X | | | X | X | | | | X | X | X | | | X | | | | | | | X | | | | | | | | | | | | | Application of BIM to university building maintenance to improve information access and intervention times | Fragmented and poorly digitized FM processes |
| BIM036 | X | | | | X | X | | X | | | | X | | X | | | | | | | | X | | | | | | | | | | | | | Application of BIM to the infrastructural design of the Paniga tunnel | Challenge in interoperability between BIM and FEM tools for structural analysis |
| BIM037 | X | | | | X | X | | | X | | | X | X | X | X | | | | | | | X | | | X | | | | | | | | | | Use of BIM and SIM to improve reliability, resilience, and adaptability of railway projects | Scope changes during the construction phase; need for probabilistic approaches to cost estimation |
| BIM038 | | X | | | X | X | X | X | | | X | X | | X | | | | | | | | X | | | | | | | | | | | | | Energy analysis and optimization through masonry materials with BIM | Need for tools to integrate simulation and BIM design |
| BIM039 | | X | | | X | | | X | | | | X | X | X | | | | | | | | X | | | | | | | | | | | | | Use of BIM for sustainability and energy design | Environmental impact and need for energy efficiency in the construction sector |
| BIM040 | | X | X | X | X | X | | | | | X | X | | | | | | | | | | X | | | | | | | | | | | X | | Ecomaps for the visualization of urban energy performance | No critical issues detected |
| BIM041 | | | | | | X | | | X | | | X | | | | | | | | | | | | X | | | | | | | | | | | Case study on a BIM system for prefabrication management: improvement of the information flow | No critical issues detected |
| DT042 | | X | | | | X | | | | X | | X | | X | X | | | | | | | X | | | X | X | | | | X | X | | | | Digital Twin for space management in Lazio; real-time integration for sustainability and smart working | Coordination between smart working and physical space; need for AI/IoT skills for full functionality |
| DT043 | | X | X | | | X | | | | X | X | X | | X | | | | | | | | X | | | X | X | | | | X | | | | | VEWS system for ventilation alert on university Digital Twin; COVID management and health prevention | Difficulties in calibrating safety parameters; large-scale implementation not yet tested. |
| DT044 | X | X | | | | X | | | | X | X | X | | X | | | | | | | | X | | | X | X | | | | | | | | | BIM+IoT prototype for predictive maintenance in university campuses. | Complexity of technical and organizational implementation; need for clear standards and procedures. |
| DT045 | | X | | | X | | | X | | X | | X | X | | | | | | | | | | | | X | X | | | | | | X | | | DT+IoT method for real-time sustainability assessment in educational buildings | Integration of environmental comfort, renewable production, and management decisions; need for a dynamic framework |
| DT046 | | X | X | | | X | X | X | | X | X | X | | X | | | | | | | | | | | X | | | | | | | X | X | | 3DStock method for modeling and simulating energy consumption of entire building stocks | Complexity in accurately representing spatial data and building-premise relationships; need for confidential data (e.g., socioeconomic). |
| IT047 | | | X | X | | | X | | | X | | X | | X | | | | | | | | | | | | | X | | | X | | | | | Integrated approach to absorptive capacity, transformative leadership, human resource development, and knowledge management | Lack of operational models for the public sector in digitalization; weak connection between theory and practice |
| IT048 | | | X | | X | | X | | | X | X | X | X | | X | | | | | | | | | | | | X | | X | | | | | | EU integration between roaming, WiFi4EU and smart city; participatory approach; focus on interoperability | Interoperability challenges, data privacy, need for multilevel coordination among entities |
| IT049 | X | X | | | X | | X | X | | | | X | X | X | X | | | | | | | X | | | | | | | | | | | | | Development of a framework for the pre-contractual phase to help select the most suitable BIM tool according to public client maturity and contract value | Low market maturity, difficulties in selecting BIM tools suitable for public clients |
| IT050 | | | X | | | X | | | | | X | X | | | X | | | | | | | | | | | | X | | | | | X | | | Integration of BPM and KM supported by IT systems, data-driven decisions, use of digital technologies for knowledge management | Low awareness of the potential of IT systems, lack of integration between processes and knowledge in organizations |
| IT051 | X | | | | X | | X | | X | | | X | | X | | | | | | | | | | | | | | | | | | X | X | | SBM super-efficiency model, use of statistical tools to assess multiple impacts on green innovation | Spatial heterogeneity in green innovation efficiency; critical role of external factors such as legislation and FDI |
| IT052 | | | X | X | | | | | | X | X | | X | | X | | | | | | | | | | | | | | | | | | | X | Adoption of blockchain by the Dubai government; development of transparent digital public services | Immaturity of the technology, need for adequate policies to support adoption |
| IT053 | | | X | | X | | X | | | X | | X | X | | X | | | | | | | | | | | X | X | | | | | | | | Framework “Civil City” con approccio pentahelix (PA, industria, ricerca, società civile, cittadini); uso sinergico di ICT e NBS | No critical issues detected |
| IT054 | | X | | | X | | X | X | | | | X | X | X | | | | | | | | | | | | | | | | | | | X | | Joint LCC–CO2 evaluation, use of digital tools for sustainable selection in procurement | Complexity of monetizing environmental externalities; lack of clear criteria for decision-making in PPPs |
| IT055 | X | | | | | X | X | | X | | | X | | | X | | | | | | | X | | | | | | | | | | | | | Support policies, staff training, team-based structures, clear job descriptions | The most effective measures are not the most adopted; lack of a coherent strategy in the public sector for BIM |
| IT056 | X | | | | X | | X | | | X | | X | | X | | | | | | | | | | | | | X | | | | | X | | | Barrier analysis via ISM, database for demand and supply, stakeholder involvement | Centralized governance model; need for new institutional arrangements and public scientific awareness |
| IT057 | X | | | | | X | | | X | | X | | | X | X | | | | | | | | | X | | | X | | | | | | | | DCIM systems for the digital management of information in the ...executive phase; survey among professionals to verify effectiveness | Low adoption by public agencies; misalignment between expectations of different types of public clients |
| IT058 | | X | | X | X | | | X | | | | X | | | X | | | | | | | | | | | | | | | | | | | | Analysis of pro-WMC policy narratives; highlighted the importance of shared visions to govern innovation | Lack of coordination among actors; fragmented governance of the technological innovation system |
| IT059 | X | | | | X | | X | | | X | | | | X | X | | | | | | | | | | | | | | | | | | X | | Relational analysis among stakeholders, use of SNA for sustainability in PPP in the water sector | Need to strengthen management capacity, awareness and technological innovation; fragmentation of stakeholders |
| IT060 | | X | | | | X | X | | | X | | X | | | X | | | | | | | | | | | X | X | | | | | | | | Innovation in business models oriented to SDG3, public–private collaboration for smart retrofits | Difficulties in creating a market for smart solutions; need for cross-sector collaboration |
| IT061 | | X | X | X | | | X | | | | | X | | X | | | | | | | | | | | | | | | | | | | | | Use of planning tools, incentives, green roofs and energy efficiency to increase urban resilience | Real estate sector exposed to extreme climate events; lack of a strong and coherent regulatory framework |
| IT062 | | | X | | | X | X | | | | X | | X | | | | | | | | | | | X | | | X | | | X | | X | | | Plantech program to digitalize urban planning, with automated workflows and openness to the public | Resistance to digitalization in regulatory processes; difficulties in updating the urban permitting system |
| IT063 | | | X | | | X | X | | | | X | X | X | | | | | | | | | | X | | | | X | | | | | X | | | Use of Big Data and GIS for urban planning and multi-level territorial management | Need for greater training and an active role of universities in managing urban data |
| IT064 | X | | | | X | | | | X | | | X | | | | | | | | | | | | | | | | | | | | | | | EU-funded frameworks, multi-stakeholder participation, training for public officials | Dependence on project continuity; difficulty involving small municipalities and peripheral areas |
| IT065 | | X | | | | X | X | X | | | | X | | | X | | | | | | | X | | | | | | | | | | | | | Smart city platform integrating sensors, apps, and dashboards for real-time management | High integration costs and maintenance of platforms over time; data privacy and cybersecurity issues |
| IT066 | X | | | | | X | | | X | | | X | | X | | | | | | | | | | | | | | | | | | | | | IoT-based monitoring of indoor environmental quality in public buildings | Need for calibration and maintenance of sensors; variability of indoor conditions due to user behavior |
| IT067 | X | | | | X | | X | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | Digital twin for scenario analysis in maintenance and energy management | High initial investment for building the DT; data quality and interoperability constraints |
| IT068 | X | | | X | | | X | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | Open data portals and civic participation tools for transparency and co-creation | Data quality and update challenges; ensuring effective citizen participation |
| IT069 | X | | | | | X | | X | X | X | X | X | | | X | | | | | | | X | | | | | | | | | | | | | Integration of BIM–GIS for infrastructure asset management over the life cycle | Interoperability issues between BIM and GIS; need for shared standards |
| DP70 | | X | X | | | X | X | X | | | | X | X | | X | | | | | | | | | | | | X | | | | | | X | | OneStop platform to simplify public–administration interaction; optimization of decision-making processes | Standardization risks that exacerbate inequalities; lack of personalized interactions. |
| DP71 | | | X | | | X | X | | X | | X | X | | X | X | | | | | | | | | | | | X | | | | | X | | | Implementation of digital capabilities (big data, interactive communication, automation) to improve agility and performance in public services | The effectiveness of technologies depends on change management that supports the technical and adaptive capacities of public staff. |
| DP72 | X | | X | X | | | | | | | | | X | | X | | | | | | | | | | | | X | | | | | | | | Inclusive strategies in the digitalization of public transport | Digital inequality and difficulties in accessing digitalized services |
| DP73 | | | X | | X | | X | | | | | | | | X | | | | | | | | | | | | X | | | | | | | | Definition of a participatory engagement model in the digital public healthcare sector | Structural difficulties in implementing effective participatory processes due to entrenched managerial assumptions. |
| DP74 | | | X | | X | X | | X | | | X | | | | X | | | | | | | | | | | | | | | | | | | | Strategic analysis of the role of stakeholders in the digital transformation of the Indian sector | Lack of applied case studies on the mentioned technologies |
| DP75 | | | X | X | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | SWOT analysis of the impacts of digitalization | Ambiguous ethical and environmental effects, limited application in construction |
| DP76 | | X | | X | X | X | | X | | X | X | X | | X | | | | | | | | X | | | | | X | | | X | | | | | Digital roadmap for healthcare FM management in Qatar with a focus on AI | Scarcity of human and technological resources, need for organized adoption |
| DP77 | | X | | | X | X | | X | | X | X | X | X | | X | | | | | | | X | | X | | | | | | | | X | | X | Development of an ICT application with BIM and Blockchain to improve transparency and traceability | Complexity in the adoption and integration of technologies in the construction supply chain |
| DP78 | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | | | X | | | | | Macro vision of digital transformation post-pandemic with a focus on AI and digital twin | Complexity in the adoption and integration of technologies in the construction supply chain |
| DP79 | | X | | | X | X | | X | | X | X | X | | X | | | | | | | | | | | X | X | | | | | | X | | | Framework based on Digital Twin and IoT for real-time sustainability assessment in university buildings | Integration of sensors, standards, and user behaviors is complex |
| DP80 | | X | | | X | X | | | | | | X | X | | | | | | | | | X | | | | | | | | | | | | | BIMReL library with CPR attributes and UNI 11337 data structure for digitalized building products | Lack of a harmonized European standard and extensive fragmentatio |
| DP81 | | | X | | X | | | | | | | | X | | X | | | | | | | | | | | | X | | | | | | | | Peer-to-peer infrastructure (Rome Makers) for participatory design and social innovation | Lack of funding and institutional support, fragile ecosystem |
| DP82 | X | X | | X | | X | | X | X | | | X | X | | X | | | | | | | X | | X | | | | | | | | | | | Mandatory adoption of BIM in the United Kingdom; focus on interoperability and data sharing through common environments | Unclear definitions of BIM Level 2; difficulties in implementation and professional adaptation |
| DP83 | | | X | | | X | X | | | | | | X | | X | | | | | | | | | | | | | | | | | | X | | Use of visual analytics for multi-channel engagement with urban stakeholders; narrative approach in data. | Difficulties in integration between channels and lack of adequate models for parallel visual design |
| PROC84 | | X | | | | X | X | | | | | | X | X | | | | | | | | | | | | | | | | | | X | X | | Use of posets for multidimensional analysis of poverty | Ineffective eligibility criteria for social measures; building obsolescence |
| PROC85 | | X | | | X | | | | X | | | | | X | | | | | | | | | | | | | | | | | | X | X | | 3-phase model for VOM | Combined impact of inadequate documentation and stakeholders |
| PROC86 | X | | | | X | | X | | | | | X | X | X | | | | | | | | X | X | | | | | | | | | | | | The public and private sectors in Australia offer innovative products and working methods when given the opportunity. | Ambiguity of information used in decision-making; Difficulty in effectively determining value-for-money in bid evaluation. |
| PROC87 | | X | | | X | | | | X | | X | X | | X | | | | | | | | | | X | | | | | X | | | X | | X | Blockchain–BIM application for green retrofitting | Increased costs in green retrofits, need for integrated solutions |
| PROC89 | X | | | | | X | | | X | | X | X | | X | | | | | | | | | | | | | | | | | | X | | | Document management for waste reduction | Inadequate communication = material waste and inefficiency |
| PROC90 | X | | | | | X | | X | | X | | X | X | | | | | | | | | | X | X | | | | | | | | X | | | Remodelling in a CDE and GIS environment, interoperability with public maps | Generic BIM standard poorly suited to complex infrastructure |
| PROC91 | | | X | | | X | | | X | X | | | | X | X | | | | | | | | X | | | | | | | | | X | | | Local strategy with CDW site controls, frequent supervision | Absence of structures and habits for waste separation in small municipalities |
| PROC92 | | | X | X | | | | | | X | | X | | X | | | | | | | | | | | | | | | | | | X | | | Stakeholder engagement, awareness and regulatory enforcement | Lack of CDW infrastructure, low awareness, poorly enforced laws |

**Figure A3.** *Cont.*

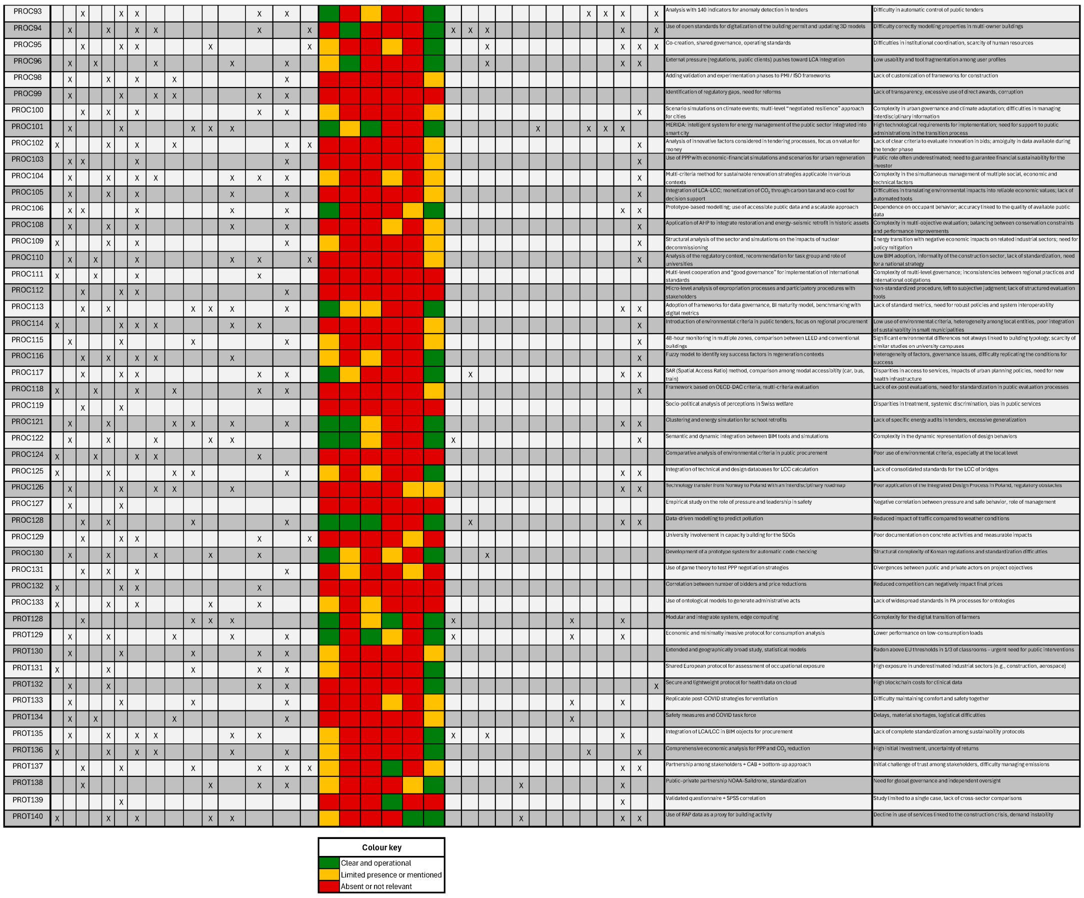


**Figure A3.** Full matrix.

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