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Review

Systematic Literature Review of Open Infrastructure BIM

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Abstract: Representation and modeling using the building information modeling (BIM) methodology of civil works have become the subject of increasing attention in recent years, thanks to the potential offered by Open Infrastructure BIM (I-BIM). However, the complexity of infrastructure works, i.e., the variety of construction and technological systems, makes Open I-BIM very complex and challenging. The lack of systemic knowledge on the subject is another challenging factor. The aim of the following research work is to provide a synoptic overview of the existing scientific research, accompanied by the most recent studies in the field of computer modeling, its applications, and the main opportunities that Open I-BIM offers to the infrastructure sector. After a thorough review of 198 scientific articles published between 2013 and 2023, this study systematically presents a holistic review and critical reflection on the current status of the use of Open BIM in the infrastructure sector, with a focus on the development of the tools and methods used. The outcome of this work constitutes a systematic review of the literature with a bibliometric analysis on Open I-BIM, which is able to provide a knowledge base for identifying research trends, common problems, and the potential of developed methods.

Keywords: bibliometric analysis; I-BIM; IFC; infrastructure; interoperability; literature review; methodology; Open I-BIM; Open Infrastructure BIM; transport infrastructures

Citation: Salzano, A.; Intignano, M.; Mottola, C.; Biancardo, S.A.; Nicolella, M.; Dell'Acqua, G. Systematic Literature Review of Open Infrastructure-BIM. *Buildings* **2023**, *13*, 1593. https://doi.org/10.3390/buildings13071593

Academic Editor: Jorge Lopes

Received: 31 May 2023
Revised: 15 June 2023
Accepted: 20 June 2023
Published: 23 June 2023

1. Introduction

Open I-BIM is a methodological approach for information flow management throughout the infrastructure life phases of planning, designing, building, operation, and dismission that leverages open standards to allow maximum collaboration among professionals and stakeholders involved in a project.

Research aims to find solutions for the full dissemination of Open BIM in the field of infrastructure (transport infrastructure, energy infrastructure and public utility infrastructure), which at present reveals binding conditions that prevent the complete digitization of works in this sector. The latest research trends are consistent with objectives that are to be found in the definition, design, implementation, and testing of innovative online services for the visualization and interrogation of I-BIM virtual digital models in a cloud sharing environment with a single collaborative shared view, thereby overcoming the evolutionary delays and technological limitations of current viewers.

Another objective set lies in the use of advanced graphic techniques in the construction of information processes for large files in Industry Foundation Classes (IFC) format for both immersive virtual reality and real-time rendering; these processes are intended to produce new operational design methodologies and ways for various stakeholders to use digital models, and for point cloud and geographic information systems, which are advanced visualization technologies integrated with frameworks for surveying and geolocation processes.

Advanced applications have been developed for the integration of facility management functions into innovative visualization systems. Methods have been researched based on Open I-BIM, in the light of I-BIM data specifications, in relation to specific purposes (ref. part IV—Standard UNI11337), and with reference to the different phases of the life cycle of infrastructural works.

These lines of research target the extension of the application of the BIM methodology in a widespread manner in the infrastructure sector by guaranteeing the visualization of I-BIM models and the use of the related data to the various stakeholders (users of the asset, maintenance workers, construction company workers, engineers, administrators, etc.) who intervene for different purposes in different places, with different technologies, and even simultaneously on the same infrastructure work.

To date, countless studies have been conducted to encourage the introduction of BIM to the infrastructure sector, with applications on roads, bridges, tunnels, and in the construction industry in general [1,2].

Nevertheless, this field of research is destined to develop further, alongside incessant technological progress in the digital sector.

The advantage of using the BIM methodology for infrastructure is that it translates into systematic project management of the entire life cycle, from planning to maintenance [3,4], and means improved collaboration between stakeholders during the design and construction phase [5], increased project quality, and increased productivity and workflow through reducing errors, and the time and resources required.

In this regard, the trend of investing in infrastructure has been recorded on an international scale in countries such as the US, Germany, the UK, India and South Korea, through strategic policy choices. Many scholars agree that there are numerous advantages to sharing computerized models through the interchange achieved by using the international standard formats, IFC and/or Extensible Markup Language (XML), which are then shared in the common data environment for infrastructure projects [6].

To conclude, in order to draw up a systematic analysis, the article consists of a review of the most recent and influential studies conducted in academia on the international scene, i.e., scientific publications pertaining to Open I-BIM, and the implementation of BIM for 3D modeling, for design, and for the analysis of the real consistencies of existing infrastructure assets, with particular reference to the civil engineering sector. In addition, this research work offers the opportunity to investigate the methods, tools, and state-of-the-art technologies for the acquisition, management, exchange, and sharing of computerized models. In addition, the study presents an annotated list of knowledge and software used for 3D modeling and data management relevant to infrastructure heritage.

2. Research Goals

The objective of the following research is to offer a systematic review of the current scientific landscape concerning the latest developments in university studies that can outline the conceptual palimpsest on Open I-BIM, based on knowledge, skills, and competences that best demonstrate the functionality of this approach and help to broaden our understanding of the potential and criticality of current methods, tools, and emerging technologies in the entire virtualization process of new and/or existing infrastructure works.

In this regard, this research activity represents a necessary sifting process, conducted based on a filter that recognizes the most influential and current scientific publications in the sector. This text aims to offer a review of the most recent scientific literature concerning Open I-BIM, outlining the state of the art in the civil construction sector.

The aim of this review is to provide experts, professionals, and practitioners in the field with a comprehensive and up-to-date overview of the research carried out on this design and information management method.

The literature review is, in general, an essential tool to identify trends and areas of research that are still under-explored, to identify open issues, and to propose new perspectives for analysis and future research directions.

3. Literature Review Methodology

This review examines studies related to the implementation of Open I-BIM, the management of information during the civil construction life cycle, the use of virtual and augmented reality to improve communication and data sharing between team members, the integration of BIM of temporal and spatial information for site safety purposes, and the complexity of BIM's dimensions and domains.

Considering that the scientific literature about Open I-BIM in the civil construction sector is very vast and covers various aspects, the research method used considered parameters to delimit the field of investigation suitable for deriving a systematic review. In this regard, the applied methodology takes into account the method of publication sorting performed by Jang et al. (2021) [6] for drafting a literature review on BIM platforms, the method performed by Lopez et al. (2018) for a literature review inherent to H-BIM [7], the method performed by Matarneh et al. (2019) for a literature review inherent to BIM for FM [8], the PRISMA protocol method performed by Regona et al. (2022) [9], and the method performed by Yao et al. (2022) [10].

The scientific literature search was conducted on Scopus, a web-based platform of reference for scientific information, drawing on search results, articles, and scientific publications that include in the title, abstract, and author keywords words that are significant and salient to the objective of the following research. It should be stated that the data shown were collected in April 2023.

The choice of search engine was Scopus by Elsevier, as it is considered by the bibliometric community to be a valid tool for accessing scientific information, due to its ability to collect publication data, track citations, and create metrics. It has been identified as a better bibliographic–bibliometric database of abstracts and citations from scientific literature and authoritative web sources than even Web of Science [11,12]. Furthermore, Bosman argues that among academic search systems, Scopus is currently the most comprehensive search engine, as it guarantees (with the option "analyze search results") interesting analytical functionalities and offers solid information on scientific knowledge [13]. In addition to this, Scopus offers greater accessibility, and allows filters to be added to searches. The following terms were used in the search strategy: ["Open BIM" and ("Interoperability*" or "Methodology*" or "Transport Infrastructures")].

Table 1 schematizes the sorting methodology performed through the following parameters: specific range, language text, type research, subject area, manual check, identification I, identification II, duplication check, and full text analysis. As shown in Table 1, entering 'Open BIM' in the search bar and specifying that this word is only present in the 'title, keywords and abstract' resulted in 971 articles. At this stage, therefore, conference proceedings, chapters, book sections, and books were excluded. Subsequently, the filters of specific range, language text, type research, and subject area were added, thereby obtaining 259 papers for which the manual check was performed. By 'manual check', we mean an accurate check of the results that involved the task of excluding 'non-relevant topic'-based articles, i.e., those not in the field, and articles published in scientific journals with an impact factor of < 0.5.

Table 1. Methodology flow diagram.

Phases and filters	**Results**		
Recounts data extracted in April 2023	Open BIM (only title, keywords and abstract) ↓ (*n*= 971)		
Specific range	2013-2023 ↓ (*n*= 833)		
Language text	English text ↓ (*n*= 796)		
Type research	Scientific article and Review ↓ (*n*= 355)		
Subject area	Engineering and Computers sciences ↓ (*n*= 259)		
Manual check	Non-relevant topics Only remarkable papers were chosen (SJR ≥ 0.5)		
Identification I	Articles identified through Scopus databases searching		
	↓	↓	↓
Main topic	Interoperability	Methodology	Transport Infrastructures
(*n*= 155)	(*n*= 38)	(*n*= 87)	(*n*= 30)
Identification II	Articles identified through journals' databases searching		
	↓	↓	↓
Main topic	Interoperability	Methodology	Transport Infrastructures
(*n*= 43)	(*n*= 11)	(*n*= 20)	(*n*= 12)
Duplication check	Duplicates deleted Only remarkable papers were chosen (SJR ≥ 0.5)		
Full text analysis	Reviewed publications (*n*= 198)		

Proceeding in this way, the 'identification I' phase resulted in 155 articles relating to Open BIM, which were divided into three topic categories: interoperability, methodology, and transport infrastructures. Following the "identification I" phase, it was deemed necessary to carry out a second identification phase that included scientific articles taken from specific databases of scientific journals, so that the articles searched using the keywords associated with the topics would contribute to obtaining an up-to-date view of the state of the art of the Open BIM sector to offer the reader.

The "identification II" phase considers further searches in scientific journal databases with a high impact factor, specifically SJR ≥ 0.5. Following "identification II", which added 43 publications, themselves divided into 11 for interoperability, 20 for methodology and 12 for transport infrastructures, a duplication check was carried out, i.e., elimination of the records common to the two identification phases (I and II).

Only noteworthy scientific publications with an SJR value ≥ 0.5 were selected for full text analysis. After detailed selection, the number of articles representing the text corpus amounted to 198 publications. Below, the flow chart schematizes the data collection and selection performed in Figure 1.

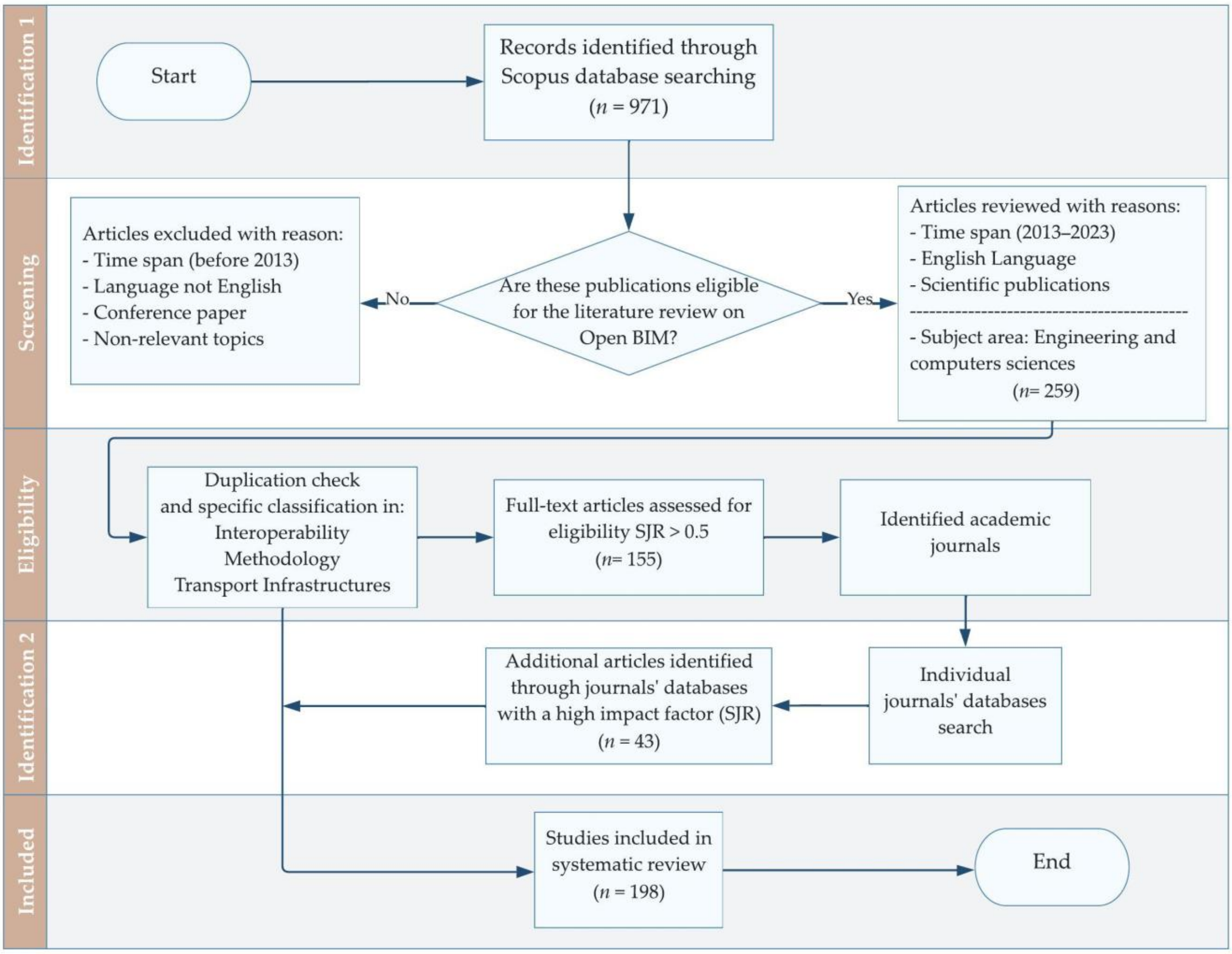

Figure 1. Flow diagram of selection of articles for analysis and review.

The selected articles belong to scientific journals with a relevant impact factor. The basic bibliometric indicator chosen is the Scimago Journal Rank (SJR). It measures the degree of influence of a scientific journal and is calculated from citation data extracted from the Scopus database. Specifically, the SJR is calculated both by counting the number of citations and by assessing the prestige of the journal from which the citation originates, thereafter assigning a different 'weight' to the citations according to provenance, using an algorithm similar to Google's search engine PageRank.

The algorithm assigns a higher weight to journals receiving citations from journals with a higher SJR.

Figure 2 shows the trend of publications over the last decade, broken down by topic, highlighting that there has been increasing interest in the subject since 2013.

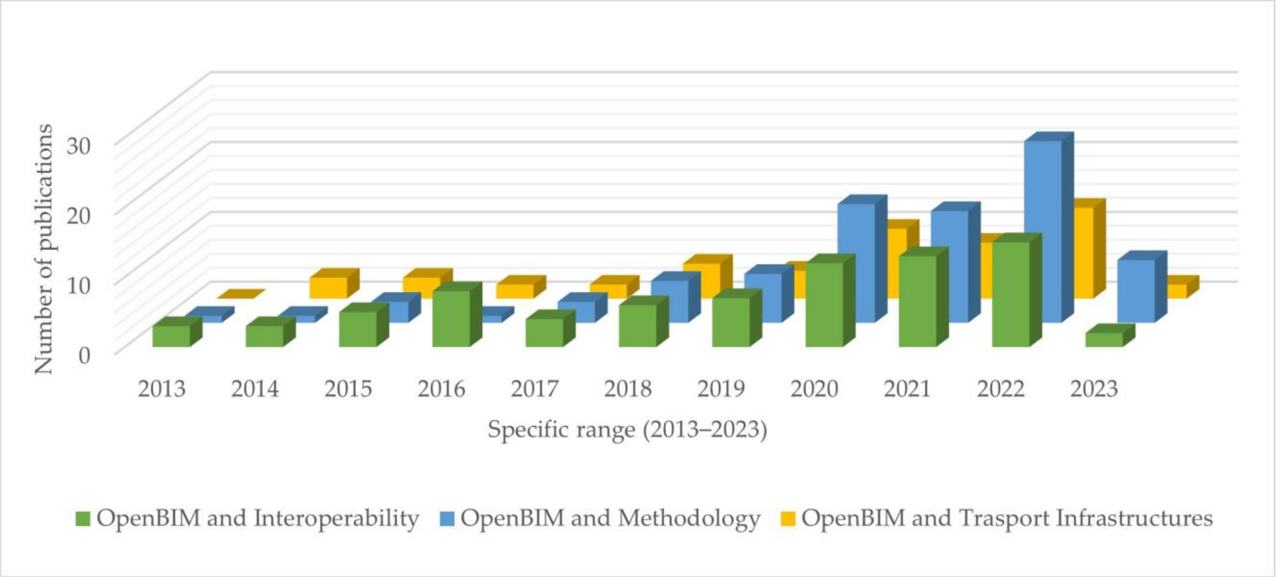

Figure 2. Histogram showing the relationship between the year of publication and the number of publications for each topic.

Table 2 shows the scientific journals, the main topics covered, the impact factor and the number of articles resulting from the detailed selection of each journal.

Table 2. Flow of publication.

Journals	Main Topic	Impact Factor*	n. of selected publications
1. Automation in Construction	Building and Construction	2.401	60
2. Applied Sciences	Facility Management	0.507	28
3. Sustainability	Sustainability and the Environment	0.664	14
4. Infrastructures	Civil and Structural Engineering	0.516	10
5. Buildings	Construction activities	0.565	10
6. Archives of Computation Methods in Engineering	Computer Science Applications	1.616	4
7. Visualization in Engineering	Computer Graphics and Computer-Aided Design	1.894	6
8. Computer-Aided Civil and Infrastructure Engineering	Computer Science Applications	3.134	6
9. Computers in Industry	Computer Science	2.427	6
10. Journal of Information Technology in construction	Computer Science Applications	0.554	7
11. Journal of Computing in Civil Engineering	Civil and Structural Engineering	1.343	8
12. Journal of Cleaner Production	Environmental Science	1.921	2
13. Applied Geomatics	Engineering	0.538	1
14. Advanced Engineering Informatics	Information Systems	1.601	8
15. Engineering, Construction and Architectural Management	Civil and Structural Engineering	0.717	2
16. Energies	Engineering	0.653	6
17. Multimedia Tools and Applications	Media Technology	0.716	1
18. Heritage Science	Computer Science Applications	0.634	1
19. International Journal of Geographical Information Science	Information Systems	1.144	1
20. Visual Computing for Industry, Biomedicine, and Art	Computer Science	0.710	1
21. Energy and Buildings	Building and Construction	1.682	2
22. International Journal of Architectural Heritage	Conservation	0.640	2
23. IEEE Sensors Journal	Instrumentation	0.926	1
24. Journal of Computational Design and Engineering	Engineering	1.034	2
25. Advances in Structural Engineering	Civil and Structural Engineering	0.692	1
26. Construction Innovation	Computer Science	0.829	4
27. Advances in Engineering Software	Software	0.920	1
28. Journal of Management in Engineering	Engineering	1.619	1
29. KSCE Journal of Civil Engineering	Civil and Structural Engineering	0.510	1
30. Steel Construction	Building and Construction	0.617	1
31. Facilities	Building and Construction	0.556	2

32. Journal of Civil Engineering and Management	Civil and Structural Engineering	0.597	1
33. ISPRS Journal of Photogrammetry and Remote Sensing	Computer Science Applications	3.481	1
34. Building and Environment	Environmental Engineering	1.498	3
35. Journal of Building Engineering	Engineering	1.164	1
36. Innovative Infrastructure Solutions	Building and Construction	0.512	1
37. Structural Concrete	Building and Construction	0.918	1
38. International Journal of Construction Management	Engineering	0.719	1
39. Industrial Management and Data Systems	Computer Science Applications	1.006	1
40. Fire Technology	Safety, Risk, Reliability and Quality	0.789	1
41. IEEE Transactions on Intelligent Transportation Systems	Computer Science Applications	2.111	1
42. Journal of Construction Engineering and Management	Civil and Structural Engineering	1.070	1
43. Computer Applications in Engineering Education	Computer Science	0.594	1
44. IEEE Access	Engineering	0.927	1

* Impact Factor according to: (SJR) Scimago Journal & Country Rank.

In light of the above, the present literature review, inherent to this research work on Open I-BIM, is structured into several stages of identification and manual control mainly based on three fixed parameters:

1. Specific time interval (2013–2023);
2. Scientific journal articles;
3. Articles written in English.

Analysis of the corpus of publications led to the identification of the most frequently used keywords, which made it possible to categorize the corpus into three main topics.

The main topics and keywords searched in the title, abstract and author keywords are schematized in Table 3.

Table 3. Keywords for the Open I-BIM main topics.

Main topic	Keyword
Interoperability	Building information modeling
	BuildingSmart
	Industry Foundation Classes (IFC)
	Modelling practice
	Data management
	Construction management
	Systems engineering
Methodology	BIM Authoring
	Viewers
	OpenSource
	Ontology
	Digital twin
	Facilities Management
	Scan to bim
	Bim to bim
Transport Infrastructures (case studies)	Road
	Railway
	Bridge
	Tunnel
	Waterway

The search recorded an increased use of the keywords, which were then grouped into main topics.

In support of this analysis, this aspect was researched with in-depth examination of data taken from Scopus, and re-elaborated with VosViewer software to obtain visual organizers capable of graphically transferring the trend of the studies conducted in the last decade by highlighting the co-occurrence keywords chosen by authors of scientific publications, using network, overlay, and density visualization (Figures 3–5).

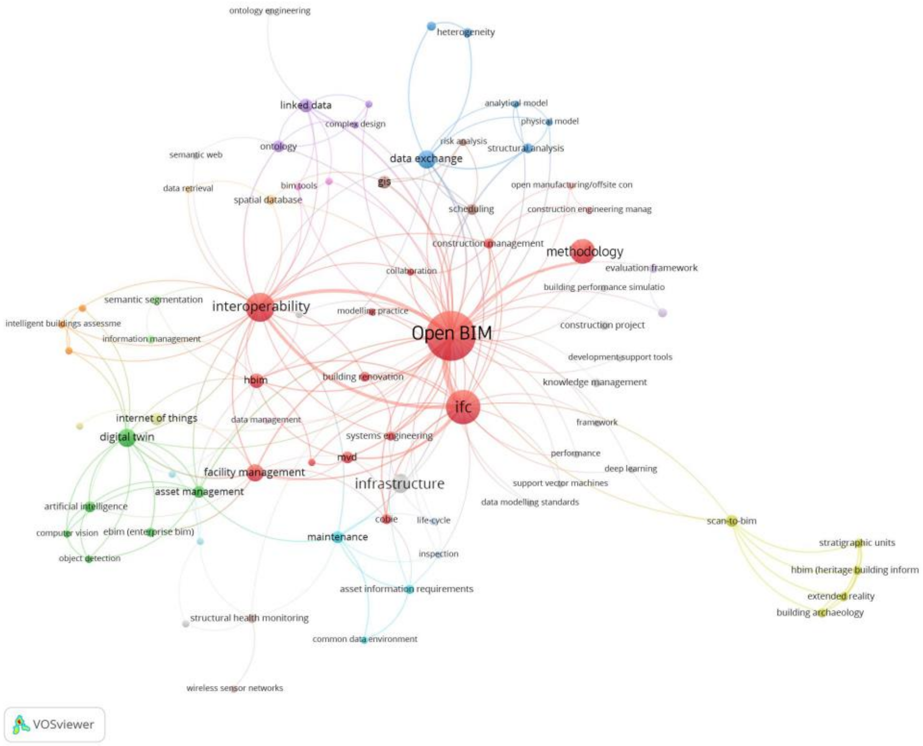

Figure 3. Keyword co-occurrence analysis with network visualization.

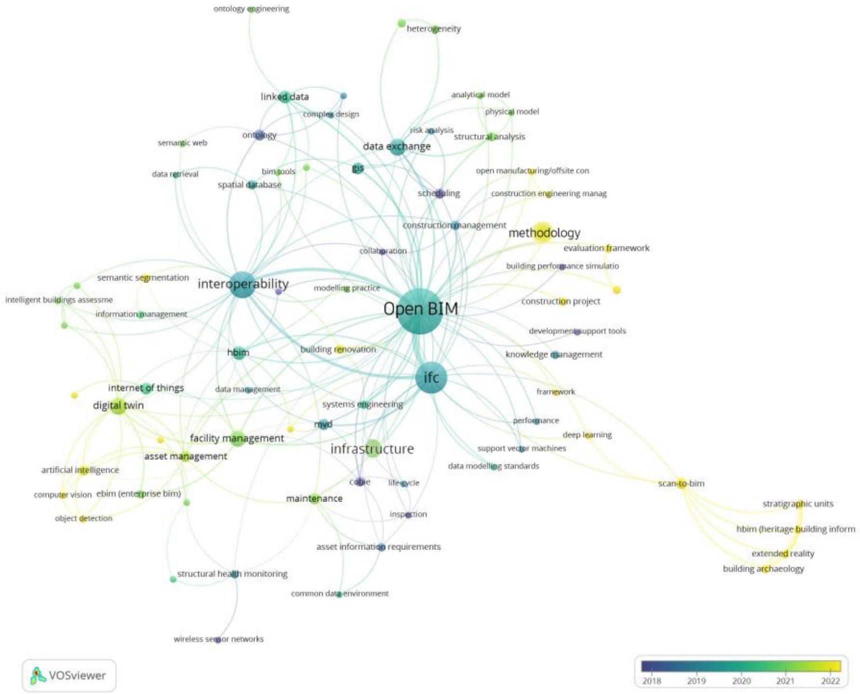

Figure 4. Keyword co-occurrence analysis with overlay visualization.

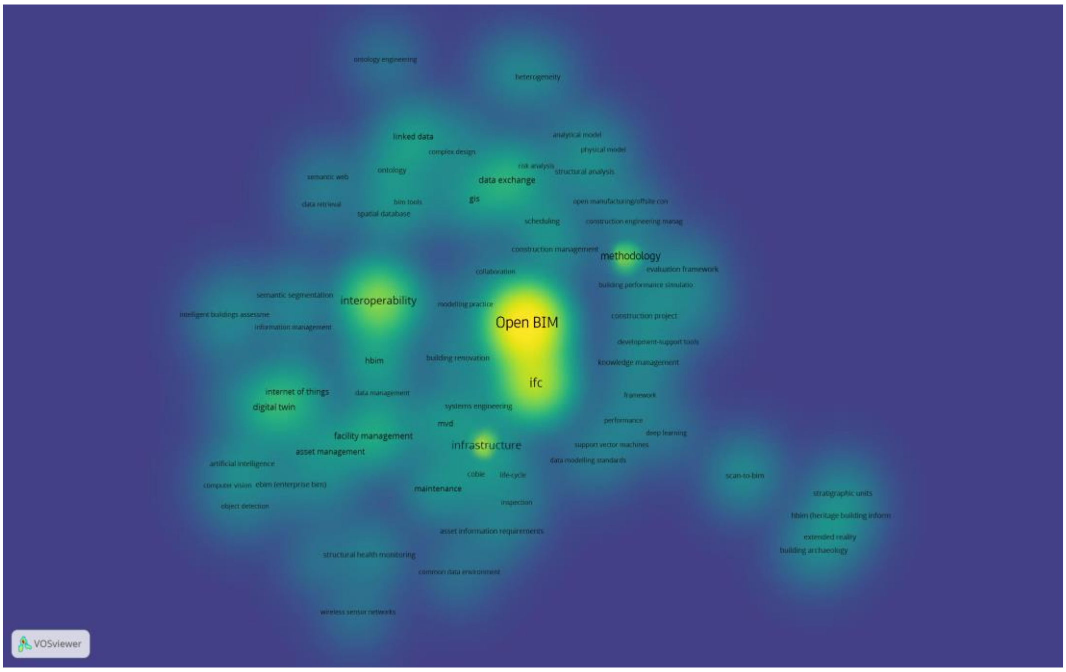

Figure 5. Keyword co-occurrence analysis with density visualization.

In conclusion, the proposed systematic research method enables a critical and comprehensive review to be compiled, with the intention of adding an additional piece, which is necessary to delimit the research field.

Within this text, a systematic literature review on Open I-BIM and innovative techniques suitable for infrastructure life cycle management is presented.

4. Background Research

The purpose of this paragraph is to provide a preparatory knowledge framework to circumscribe the scope of the specific topics of the review. The following sub-sections outline the state of the art regarding definitions, methodologies, case studies, and the different uses of I-BIM and Open I-BIM.

4.1. Definition of I-BIM and Open I-BIM

Building information modelling (BIM) is a methodological technique that results in the digital depiction of the structural and functional elements of a building or infrastructure. In order to replicate the design, construction, and use of infrastructure, a 3D interactive model must be made and used [14]. The I-BIM model includes data on every component of a building, including geometry, material specifications, cost projections, and energy performance information [15].

However, I-BIM presents unique challenges, as its adoption requires a shift to a different way of working, not only compared to the traditional Architecture, Engineering, Construction and Operation (AECO) industry, but mainly due to the gaps in the adoption of BIM in EU and non-EU countries, and the barriers to its implementation [16,17]. In the presence of fragmented and badly integrated projects [18], there are negative consequences, particularly in terms of energy efficiency, costs, sustainability, resourcing, and safety [19]. On the other hand, the origins of BIM can be found in the 1970s, when early CAD programs were created and applied to the design of buildings and engineering systems. The use of CAD software to combine the advantages of two-dimensional architectural design representations (drawings, plans, and sections) and three-dimensional representations (physical models made of hardboard, plastic, and other materials) in a single digitally realized model was pioneered by Charles Eastman, who is widely regarded as the father of BIM [20]. The researchers van Nederveen and Tolman (1992) [21] coined the term BIM for the first time, and the software corporation Autodesk expanded its use by publishing a white paper in 2003 [22]. The arrival of new technologies ensures better awareness of these issues, while preserving and protecting the environment and built heritage. In this context, in order to cope with the increasing scale and complexity of projects, it has been necessary to improve the interoperability of information between multiple disciplines and between different software platforms [23].

Interoperability is all about information exchange, but this needs to be regulated so that professionals have guidance on how to share information in the most streamlined, efficient, and useful way. ISO 19650 is the technical standard that regulates the I-BIM process, including information flow. Thus, once a project's objectives have been defined, the uses of the model are derived according to the logical correspondence to the information requirements. This gives rise to the concept of Open I-BIM, which is opposed to ClosedBIM. While ClosedBIM uses software from a single manufacturer with a single native proprietary format for data exchange [24], Open I-BIM is characterized by the use of open formats for data sharing, which make the construction process more collaborative.

Although IFC has a relatively long history—the first version was released in 1996—when it comes to linear horizontal infrastructures, such as roads and railways, only the most recent official version, IFC 4.0, ISO 16739-1: 2018, offers classes and modules for effective data transmission and geometry representation. Indeed, there are numerous studies pointing out flaws and suggesting fixes. For example, Jaud et al. [25] critically analyzed Release Candidate 1 of the IFC 4.3 standard, identifying a number of issues with linear placement, and making an improvement suggestion that was later accepted for the definition of Release Candidate 2.

Open I-BIM should be regarded as an information management system, and it is open when information from different disciplinary areas is integrated into individual infrastructure projects. This approach offers numerous advantages, such as the possibility of sharing data between different software packages and enriching the information model using different types of data. Initially focused mainly on ascertaining the potential of 3D assets digital representation, researchers are now studying more and more the other BIM dimensions, highlighting and quantifying the pros and cons of the methodology for cost estimating, sustainability, and facility management.

4.2. I-BIM and Open I-BIM Approaches

In the context of BIM modeling of infrastructure works, different approaches suitable for different cases emerge. BIM becomes I-BIM when it is applied to horizontal infrastructures such as highways and railroads. It can entail the modeling of all sub-service facilities and plants, and applies to both highways and railways [26]. While horizontal constructions are very different from punctual architectures, the concepts of the approach are the same, but the implementation is different. Indeed, the spatial orientation and extension of horizontal infrastructures implies a specific approach to geometric modeling techniques.

The augmented reality approach, for example, uses 3D images to digitally reconstruct existing infrastructure [27]. This approach often requires manual processing of the collected data, making it expensive and unsuitable for large amounts of information. Similarly, the 3D scanning (laser scanning) approach uses laser scanning technology to acquire data on the surfaces of the built object [28]. Despite this, this approach presents challenges related to the quality of the acquired data, the complexity of data modeling, and data management.

A further approach is the multi-disciplinary approach of merging the I-BIM methodology with real-time monitoring using IoT (Internet of Things) sensors. It is becoming the dominant trend in approaches to improve efficiency in the construction sector [29]. IoT sensor networks allow the connection of real-time data streams to BIM models, thus facilitating many applications. This integration of the physical and digital world by adding dynamic real-time data to a static BIM model produces digital twins (DTs).

An infrastructural digital twin (IDT) is a digital representation of a form of physical infrastructure, such as a bridge or a building, with its internal structure and components [30], which allows its performance to be monitored in real time and any faults to be predicted for maintenance. In other words, an IDT is defined as a virtual replica of a physical asset—either single or federated to other IDTs—characterized by a bidirectional data flow between virtual and real space, offering in-depth knowledge of the infrastructure. Many studies refer to the DT as a cyber–physical integration rather than a DT as understood in the narrow sense (which is considered unattainable, since it is an abstraction of a real-world model). Furthermore, there are several studies in the literature comparing DTs with the cyber–physical systems (CPSs), dividing scientific opinion on the matter into three groups [31–34].

DTs are composed of physical and virtual components and the data that connect them, representing the connection between the duality of virtual and physical reality. Furthermore, Grieves (2015) states that data derived from physical reality collect real-world data that is used for processing, and that data derived from virtual reality apply engineering models to discover information that absolves physical reality in everyday life [35]. This branch of research has been further explored in the context of the symbiotic relationship between the physical and virtual parts of a DT, concluding that BIM is often considered a sub-component. In fact, the idea of realizing a DT contains within itself the need to realize a BIM model, as it is the digital virtualization of the architectural or infrastructural asset, which is further enriched with Big Data and IoT [36].

4.3. The Different Uses of I-BIM and Open I-BIM

Research into the Open I-BIM methodology has focused on its potential for possible green and innovative solutions. Many researchers see in this methodology the possibility of reducing waste, both in terms of materials and energy, thus decreasing global pollution. The work of Zhang et al. (2022) [37] integrates the BIM methodology into the wider context of the circular economy and waste reduction in construction, proposing that the DT be at the center of a workflow for solving problems in the remanufacturing industry.

Regarding the issue of preventive maintenance, it is crucial to ensure the safety of infrastructure and prevent costly repair work. The DT allows different scenarios to be simulated and the impact of changes or interventions in the structure to be tested. In this way, maintenance work can be planned more efficiently, thereby reducing costs and increasing safety. In addition, the DT can be used to improve the sustainability of infrastructure by monitoring energy consumption and greenhouse gas emissions. Thanks to the ability to simulate different scenarios, it is possible to identify the changes needed to improve the energy efficiency of the infrastructure, thus reducing the environmental impact.

In this research context, Salzano et al. [38] highlight how BIM integrated with life cycle assessment (LCA) analysis is suitable for managing a considerable amount of heterogeneous data. It is also suitable for providing information at the design stage that can guide design choices towards sustainable design, as the environmental impact of each choice and each component included in the project is known from the outset. Open I-BIM and LCA (life cycle assessment) are central topics of environmental sustainability, supported by new technologies and methodological approaches [39]. BIM has multiple applications in the fields of architecture, structural, geotechnical and plant engineering, as well as in infrastructural, transport and hydraulic engineering. Biancardo et al. published the interesting results of their work on road design based on the BIM methodology in 2020 [40]. The research also focused on analyzing the interoperability between the various tools used. Previously, in 2017, Zhou et al. published a review paper on the potential applications of tunnel engineering in China [41]. Their study focused on some real applications of BIM designs of mountain tunnels, and then shifted the focus to a general review of the lack of well-defined standards and guidelines. Others explored the possible applications of BIM to the world of infrastructure, and in particular to underground infrastructures such as subways. Xie et al. used BIM models of underground metro works to support statistical analyses of the soil characteristics and bearing capacity of the modelled works, combining random field theory (RF) and BIM [42]. Another aspect to be emphasized is that the DT can also be used to improve infrastructure management, allowing problems to be identified before they occur, even during the on-site assembly of MiC (modular integrated construction). The MiC system integrated with a DT for on-site assembly has a lower workload, and consequently brings benefits in terms of efficiency, sustainability, and quality by significantly reducing human error [43].

The on-site assembly process can be coordinated in several stages, among which are the construction of the foundations, the installation of the MiC modules, the joining of the module, and the planning assisted by the optimization of crane-related lifting [44].

In this context, numerous studies can be regarded as inherent to construction site safety planning; these studies are focused on spatial–temporal conflicts simulated in VR (virtual reality) and allow the planning of construction site activities a priori, obviating the risk of these conflicts occurring [45]. The studies conducted by Yi and Langford [46] attempted to identify (in terms of time and space) construction site risk situations and zones by combining historical accident data and the project schedules that generated them. Mawlana et al. [47] proposed a 4D BIM model to sequentially simulate the operations required for the construction of elevated urban highways; the model was able to prevent spatiotemporal collisions using stochastic mathematical models. Meanwhile, Navon and Kolton [48] developed a safety monitoring and control schedule, such that the locations of fall hazards could be predicted. Being still related to site safety and the complexity of offsite/onsite assembly with MiC, delays in material logistics [49], and the variability of boundary conditions, the dispersion of activities and the organization of contractors should also be considered (in addition to safety) as risk factors. On-site assembly with MiC is mainly based on the real-time monitoring and control of the process, and thus the traceability, lifting and installation of the module on site [50].

In light of the case study of the modular construction of the main building of the University of Hong Kong, consisting of 28 prefabricated modules [51], the research team developed a smart MiC system enabled by a DT, and used experimentation by means of a test on an on-site assembly robot in the prefabricated construction industry. This method demonstrated how convergence and interoperability between synchronous physical and digital assembly can bring improvements in terms of reduced construction time, errors and costs, as well as increased safety for workers and facilitating managers.

Thanks to real-time data collection, it is possible to identify any malfunctions or anomalies and promptly take the necessary measures to resolve them. Using a DT makes it possible to improve the security and sustainability of infrastructure, reducing maintenance costs and improving infrastructure management.

5. Literature Review on Open I-BIM

In the following, we present the results of the analysis of the full texts deduced from the review methodology set out in Section 2. The selected articles deal with Open BIM applied to infrastructure. A systematic analysis of the articles was carried out in order to obtain a comprehensive view that met the research objectives.

5.1. Interoperability

5.1.1. Implementation of Open I-BIM and IFC

One of the aspects of the research conducted in recent years is rooted in an awareness of how tools and technologies have influenced the modus operandi by which information related to the built environment is created, exchanged, shared, and archived among stakeholders. There has been an exponential spread of integrated methods for sharing construction data following the introduction of IFC; this has changed the way tools and methods are conceived in both research and development. The IoT [52] and components of artificial intelligence (AI—data analytics, machine learning, deep learning, etc.) [53] have been integrated in tools and technologies, which is why scholars and researchers are finalizing paradigms that interconnect people, processes, and emerging technologies in a coordinated manner. This paradigm, by the way, is not to be limited to the construction sphere, but has rapidly encompassed research areas adjacent to the life cycle of the built environment, including buildings, infrastructures, and entire cities. It must be remembered that BIM, initially aimed at modeling, is now facing obstacles; the exploitation of big data, the IoT and artificial intelligence represent the missing pieces of the automation mosaic.

The reason for the exponential development in the field is the extension of the uses of BIM, which have expanded to include the life cycle management of built infrastructure assets. In this field, the study conducted by Llatas et al. (2022) focuses on the Life Cycle Sustainability Assessment, or the LCSA, proposing a systematic, interoperable and open-source approach to the implementation of this assessment in five phases. Automation of the main assessment phase is provided via the integration of IFC4. This method was applied to a case study in Spain through influencing design choices to move in the direction of less costly and more suitable structural solutions for the site, and identifying the system that emits less CO2 [54].

A study conducted by H. Li et al. [55], which proposed an information management model based on the Open I-BIM approach for monitoring and maintenance during the life cycle of bridges, has aroused great interest. Additionally, in this regard, studies have been conducted that enable the storage and visualization of inspection data so that inspection information (defect geometry, spatial location, shape representation, etc.) can be documented and represented in bridge BIM models [56,57]. Through the parametric modeling of a motorway bridge, it was possible to represent the interrelationships between defects and IFC entities, e.g., the technical elements of the bridge, root causes, and maintenance work. This method enables the representation of information on defects, with IFC facilitating the BIM environment for the purpose of civil asset life cycle management [58]. The authors analyzed the advantages of Open BIM in data and information management, emphasizing how the adoption of this approach can improve data quality, collaboration between the various actors in the infrastructure sector, and the efficiency of information management. Emphasizing the importance of obviating the loss of information, the case study conducted at the CESI Campus in Paris-Nanterre, for the realization of an intelligent building, demonstrated that IFC-based Open BIM allows for proper modeling without data loss [59]. Concerning the improvement and control of quality during the design phase, a study conducted by Häußler and Borrmann [60] proposed a standardized method to validate design quality by means of fourteen quality parameters. The results showed that the approach improved the collaboration between the various actors involved, and reduced construction costs and time by making the entire process more efficient. The authors emphasized the advantages of Open I-BIM in managing conflicts between different disciplines, information management, and process coordination. These advantages have been ascertained by studies such as that of Shin et al. (2018) [61], who demonstrated through a cost–benefit analysis the effectiveness of adapting BIM in railway construction sites for the construction of bridges and tunnels [62]. Other studies have combined the BIM method with GIS, for example, in the 4D GeoBIM system [63]. This combination ensures construction safety through the creation of three-dimensional models in a geospatial context. In order to promote the interoperability of GIS data, the study conducted by Malinverni et al. [64], analyzing the conversion methods of CityGML and IndoorGML, produced an enriched model based on the connections between different models in a GIS environment. It is an established idea that Open I-BIM plays an important role in the maintenance phase in terms of SHM (structural health monitoring) and control. Furthermore, the literature offers insights into this area, combined with the use of GIS technology. These include the BIM-3D GIS system [65] for tunnel management and the BIM-GIS framework for underground utility management systems, as well as systems combining SHM and BIM for monitoring infrastructure structures via an automated platform [66] and via VR and AR [67]. The most important aspect of the development of this technology is the interoperability of data ensured by the open formats also used for ongoing energy research. The study conducted by Choi et al. (2023) proposed a plan to generate alternatives and assess energy performance by analyzing the envelope shape of amorphous buildings through IFC [68]. Furthermore, more agile methodologies, based on the graph technique, are outlined to enable automation in the field of BEM with less inconsistency and interference [69]. The inclusion of domains not traditionally related to BIM encouraged the development of interoperability that would allow different project actors to facilitate the integration of their know-how and the import/export from one BIM tool to another.

The IFC standard was designed to solve this problem. However, at a stage close to its realization, its initial application limitations were extended into other areas. Therefore, the IFC standard, which was designed to transfer model data from one tool to another but not to be dynamically modified, has evolved significantly from the model view definitions (MVD). In addition, in relation to the implementation of the ISO-10303 Part 28 standard, Kim et al. [70] proposed a useful framework for the automatic generation of schedules from BIM, based on the international ifcXML standard schema. The scheduling approach was used to create construction tasks, considering productivity rates and sequencing rules. The practical case involved a BIM model of two separate structures modelled with basic building envelope components and exported as an ifcXML file.

In the literature, there are many ongoing pilot studies combining the capabilities of linked data (LD), web ontology language (Owl) models and IFCOwl, which offer improved interoperability. The latter represents a necessary step to ensure the correct alignment of information between different professionals through the sharing of model data on the web, achieving the goal of integration with semantic models as part of the semantic web stack. As technology is constantly evolving in parallel, research is always preparing new perspectives, among which the implementation of the Open I-BIM approach in construction projects with the use of innovative tools and technologies has received special attention [71]. Research has shown that over the past decade, the use of virtual reality (VR) and augmented reality (AR) has improved communication between the various figures involved in industrial processes in the AEC (Architecture, Engineering and Construction) [72] sector, facilitating understanding through the visualization, sharing, and exchanging of data in the cloud. The study performed by Wang et al. (2018) showed that the use of VR integrated into education programs for future engineers and architects perfects their performance in training [73]. Alizadehsalehi et al. showed that a construction process using extended reality (XR) brought about improvements in terms of communication efficiency, increased accuracy, and understanding of information, and increased user involvement in the design and construction phases [74]. Qiu et al. (2019) delved into the topic of VR linked to a DT, investigating the benefits to be derived from the combination of the two with regard to remote operations, collaborations, and virtual assembly technologies in the design phase of construction, under continuous interactive control [75].

5.1.2. Open I-BIM and Data Exchange

Following the transition of BIM into the infrastructure project sector [76,77], the design, construction, and maintenance phases of infrastructure projects have presented complex challenges mainly related to the concept of extension, linear development, and environmental compliance. To address chronic low productivity and unsatisfactory project performance, Baghalzadeh Shishehgarkhaneh et al. [78] examined alternatives to standard project delivery models and approaches. They found that failures of integration and collaboration are the fundamental reasons for unsatisfactory performance. The education sector has also aligned itself with the need to improve these aspects. Regarding the BIM transition in tertiary education, Chegu Badrinath et al. [79] state that the importance of BIM education has been recognized as of 2015 in AECO disciplines worldwide. Santos et al. [80] highlighted that the topics discussed are inherent to BIM tools, worldwide BIM adoption, and interoperability between BIM tools for different applications. One of the most critical issues remains the ability of IFC to support information exchange. Among numerous studies, Steel et al. [81] investigated interoperability in the exchange of IFC-based models between different BIM tools. Shahzad et al. [82] believe that BIM applications are more developed in design than their applications in construction and operation precisely because of interoperability challenges. Dixit et al. [83] investigated the factors hindering the integration of facilities management (FM) with BIM technology. They concluded that although the use of BIM technology has grown exponentially in recent years, unfortunately, its application to FM has not been fully accomplished. Lockley et al. [84] addressed the creation of standard building component libraries for BIM that can be shared between different BIM platforms. They also have highlighted the problem of comparing IFC models in a neutral collaboration between building information model platforms.

The critical problem in IFC models' comparison is the definition of globally unique identifiers (GUIDs). As fruitful as it can be considered, the exchange of information between BIM tools is lacking, because when exporting the BIM model to IFC, one is subject to loss of information due to data reduction, simplification, translation, and interpretation. To remedy this, neutral networks partially solve this defect by classifying the contained objects and suggesting corrections. The SpaRSE-BIM neutral network model, based on sparse convolution for geometry classification in IFC and the semantic enrichment of BIM models, is better in terms of accuracy and execution time [85]. Similarly, the study conducted by Buruzs [86] on IFC models of residential buildings with the help of a GCN(graph convolutional network) led to an improvement in accuracy because the neutral network uses information about connections and spatial context for its classification decisions. Transport infrastructures, such as roads, railways, bridges, and tunnels, require constant and continuous geographical referencing during their design and construction; it is a fundamental parameter that cannot be excluded at any stage.

Therefore, the concept of interoperability is the common denominator in the presence of road infrastructures, as it ensures collaboration and exchange between professionals, and mainly between the different pieces of software used globally. Sometimes, software coordination is also necessary between platforms relating to infrastructures that differ in type, e.g., linear works and point works. With regard to bridges, software coordination and automation for the acquisition and visualization of inspection data are useful tools. At the territorial scale, with a view to the digitization of cities, the concept of interoperability and its application, including aspects relevant to the management of an urban context, are essential. Lv et al. [87] agree that smart urban management is realized through the digital collection, transmission, processing, and visualization of physical urban data, which can only be ensured by interoperability.

Therefore, the construction of a DT urban platform can improve the perception and decision-making capacity of cities, as it simultaneously offers a broad vision for planning future interventions and a valuable tool for city governance. Musarat et al. [88] state that digitization in infrastructure construction has improved quality of life, and enhanced productivity and automation. As repeatedly mentioned, data sharing and exchange are necessary to reduce risks to people, reduce environmental impacts, and to prevent unforeseen events on the construction site by checking in advance for interference between architecture, structures, and installations. Geographic references are obtained from the geographic information system (GIS) which, integrated with the BIM model, allows for parametric modeling with additional geo-information [89].

In the context of HBIM, Zuric et al. [90], points out that for data exchange, the use of IFC allows the integration of HBIM in the certification of GBC historic buildings. It represents a valuable tool for the first prerequisite of the Certification for Sustainable Restoration. This process was tested on the Paço dos Duques in Guimaraes, Portugal. As part of the studies on VR/AR for HBIM visualization conducted by Garcia et al. [91], Osello et al. [92] present a methodology based on BIM and interoperability for converting existing buildings into intelligent buildings. The combination of BIM and ICT makes it possible to manage, visualize and adapt information about existing buildings.

5.1.3. Complexity of BIM Dimensions

In the complex landscape of Open I-BIM, studies published in the last decade highlight the registered tendency to create more efficient ways of visualizing and utilizing data from nD models, particularly with regard to site monitoring [93], health and safety [94], and environmental aspects [95], showing that as the amount of input data increases, so does the degree of complexity of the domain.

The origin of this complexity lies in the heterogeneous nature of the data's sources (tools, sensors, building management systems, etc.) that link them to the existing BIM model. The implementation of BIM reaches its peak for coordination and collaboration, unlike in the past, when it was thought that data augmentation coincided with the pre-construction and construction phases. This implementation is due to the synergy of all stakeholders converging and collaborating using a 4D BIM for activity planning and 5D for costing. The technique developed by Marzouk and Hisham (2014) combines time and cost management with the concept of earned value (EV) to determine the state of work at a specific date for the construction of a bridge through a BIM model of the bridge; this is referred to as bridge information modeling (BrIM) [96].

However fruitful such a database may be, we inevitably must consider the large amount of information produced. Moreover, much of this information built up in the various phases remains unused. It is worth emphasizing that scholars have called the excess of project data "drowning in data", with little added benefit for the construction chain [97]. This phenomenon occurrs as a result of the exponential increase in data since the adoption of BIM, especially in the design and construction phases. The portion of the structured data pertaining to the operation and maintenance of the infrastructure is transferred in the form of a COBie spreadsheet [98]. The COBie standard (Construction Operations Building Information Exchange), also definable as an IFC model view definition (MVD), has been approved by buildingsSMART International, which identifies it as a subset of IFC (ISO 16739:2013) that includes data useful for facilities management. The creation of an IDM (information delivery manual) later translated into a pilot MVD for cultural heritage in consultation with experts in restoration and conservation, as stated by Oostwegel et al. [99], highlighted developments within a model of a historic building, in which the historic building was semantically enriched with information about the conservation plan. This study demonstrates the feasibility of creating an MVD for the standardization of BIM in the cultural heritage sector. It has emerged that it is advisable to link the sources of data, information and knowledge in order to gain full benefit from nD BIM. In this area, the study conducted by Matarneh et al. [100] proposed the development of software to create an open web-based prototype that fills the gap of existing semi-automated tools, such as COBie, which lack precision in the area of manual data entry. This study highlighted the need to replicate data extracted from the IFC to the cloud server via SQL-linked servers. These studies highlight the importance of Open BIM in the civil construction sector, and its positive impact on the collaboration between the actors involved in the construction process, the management of information during the building life cycle, and the use of innovative technologies to improve communication and understanding of data. Overall, the scientific literature on Open I-BIM in civil construction highlights its benefits in terms of improved collaboration, reduced construction costs and time, and better information management during the building life cycle. However, further research is still needed to evaluate the effectiveness of the Open I-BIM approach in different contexts, and with different types of point and linear infrastructures.

5.2. Methodology

Actual use of Open BIM for infrastructures implies teams, companies, and professionals must work to adapt to a new technology and methodology paradigm. This is a real concern, and some academics have addressed in their work how we may effectively overcome the limitations of a paradigm shift [101]. Public administrations must also embark on a mission to upgrade, so that the open BIM methodology is adopted and can bear fruit. Ullah et al. [102] studied the readiness of municipalities to actually start the process for bidding, including BIM services, by exploiting a multiple-criteria decision-making method, namely Fuzzy-COPRAS. The possible social benefits directly attributable to the adoption of this methodology are the subject of the work of Shin et al. [103], who focused on the use of BIM to avoid disputes in MOBs (multi-owned buildings), and confirmed that it facilitates the alleviation of the residents' misbehaviors by informing them, with accurate communication, of their ownership rights, thus diminishing disputes. Moreover, for BIM to be Open and give the intended benefits, collaboration platforms must be developed. An exemplar is the work of Benghi C. [104], who presented a large-scale interdisciplinary collaboration platform to enhance open BIM workflows suitable for automatic quality assurance via the use of an IFC and Drools engine, which is an open-source rule engine for business rule management systems (BRMS).

5.2.1. VR/AR and AI

Part of the research on Open BIM for infrastructure addresses a certain range of technologies, such as virtual and augmented reality, to improve management procedures and generally develop advanced methodologies. In 2022, Carbonari et al. [105] published their paper demonstrating that an MR-based platform can involve interested stakeholders in the assessment of renovation design projects, speeding up the decision-making process and increasing projects' quality. Experimentation in this direction also harks back to earlier work, such as in the case of Zaker and Coloma [106], which involved BIM professionals in order to assess the limitations of applying VR in BIM, and how these issues might be overcome. However, there are many technical problems when trying to fully exploit the integration of BIM, open formats, and augmented and virtual reality technologies. For example, although virtual and augmented reality visors bring obvious advantages in the health monitoring of important infrastructures such as bridges, tunnels, and roads, and also in buildings of various kinds (even those of considerable engineering importance and weight) [107], IFC standards do not provide a description of structural health monitoring (SHM) systems. Theiler and Smarsly [108] proposed an extension of the IFC schema to bridge this gap. In the work of Chung et al. [109], dated 2021, the authors defined a tool for the conversion of BIM objects, namely doors and windows, from COBie format (Construction Operations Building information exchange) to a format that can be interpreted through augmented reality, thereby achieving an improvement in the facilities management process due to the immediacy of information transmission.

As early as 2013 [110], research looked for methods to bring site data to construction sites, and thus to on-site operators, in digital format, via augmented reality. Many methods were developed [111], and today, VR and AR viewers are widely used on construction sites for the management of construction orders [112]; web-based tools are also used [113], particularly given the central importance of cloud resources in the context of the BIM methodology [114]. The research field of technologies for the visualization and navigation of augmented reality based on BIM models is expanding, and has also been integrated with some specialized fields related to artificial intelligence [115]. For example, Chen et al. [116] published a paper describing a procedure for enhancing unmanned ground vehicles' behavior, global path planning, and collision and congested environment avoidance in indoor environments, while Musella et al. [117] exploited AI for the digitalization of seismic damage in existing buildings. AI is also used in the form of neural networks and predictive and automatic modeling, both geometric and semantic. Koo et al. [118] used two models, namely a multi-view convolutional neural network (MVCNN) and PointNet, to classify ten types of commonly used BIM elements in road infrastructure, using a dataset of 1496 3D models to enhance mapping between IFC entities and BIM elements.

5.2.2. Point Clouds

BIM provides a tool to digitally represent the built environment. Moreover, it enables the possibility of dynamically representing the building process in every phase, enhancing facilities' management, but also construction sites' management. To this end, there are very advanced supporting technologies for geometric surveying [119]. For example, laser scanning can survey any object and create clouds of millions of points within minutes. The instrument fires laser beams covering a 360° space, and measures the position of the points hit as a distance from itself, based on the time it takes for the laser beam to return to the instrument. Then, knowing the geographical coordinates of the position covered by the instrument or other notable points, the entire point cloud is geo-referenced. Each point carries information about its location, geographical coordinate system, and other characteristics such as coloring and reflectivity index. The ability of discerning objects within the point cloud to segment the point cloud is very important [120]. Laser scanners mounted on unmanned aerial vehicles (UAV) are a game changer for large infrastructures' management by means of BIM and digital data [121,122].

The two main methods based on point clouds are Scan vs. BIM and Scan-to-BIM [123,124]. Scan-vs-BIM is a monitoring method, while Scan-to-BIM is a modeling method. In fact, the first is a methodology based on comparing the characteristics of point clouds with those of the 3D models underlying BIM; these characteristics are not generated from the point cloud, but through other methods and other data. The second method consists of creating a BIM from the data contained within point clouds obtained via laser scanning.

In 2017, Reboli et al. [125] tried to define an accurate and applicable metric for evaluation of the quality of a point cloud for construction progress monitoring using the Scan-vs-BIM method. They developed a framework to evaluate hundreds of test point clouds vs. a test BIM, and a different scanning methodology to come up with the definition of the right quality criteria for successful Scan-vs-BIM identification.

Information retrieval from point clouds is a hot topic in BIM research. In 2018, Hidaka et al. [126] proposed a method for polygonising from a point cloud based on similarity. In particular, the authors' algorithm identifies objects that may belong to a same category through shape matching. In 2019, Xue et al. [127] developed a very innovative approach for detecting architectural symmetries directly from 3D point clouds. The authors formulated an automated architectural symmetry detection system as a nonlinear optimization problem, involving parameters reflecting architectural regularity and topology; then, they developed a derivative-free optimization approach for optimization-based detection of an architectural symmetries algorithm, testing it on nine sets of point clouds and achieving good results in terms of computational time and symmetries detected.

5.2.3. Semantic Technology

Works such as that of Xue et al. [128] deal precisely with the possibility of automatically identifying elements that can correspond to instances of BIM models. To do this, algorithms are used that exploit semantic technologies. Semantic technology is a set of methods and tools that, through using formal semantics, provide advanced means for categorizing and processing data. It presents the possibility of analyzing the relationships within varied datasets. It can be seen as a buffer layer between human data understanding and artificial intelligence data and information processing. Semantic technology allows us to store, manage, and retrieve information based on meaning and logical relationships. To express relevant component information and behavior that corresponds to a certain field of expertise, semantics are incorporated within objects, both geometrically and non-geometrically, using the parametric modeling capabilities of BIM software. The process of identifying possible instances of BIM models from geometric data in point clouds using semantic technologies is called semantic segmentation. Moyano et al. [129] applied semantic segmentation to retrieve data from the point cloud of the façade of the Casa de Pilatos in Seville, which is a heritage building. For a very similar purpose, Zhai et al. [130]

exploited artificial intelligence, and in particular deep learning, to automate the semantic segmentation of point clouds. Jung et al., in 2018, developed an effective method for automatic analysis and segmentation of point clouds in order to recreate the indoor environment of buildings with multiple rooms. In particular, the authors managed to reproduce various objects, such as doors and windows, and to discern between structural and non-structural elements [131]. The semantics of BIM models is a fundamental dimension of the entire methodology, fully embodying the *I* of the BIM acronym, which stands for information. Indeed, information management is an aspect that BIM research has always invested in, and it is what makes a BIM an Open BIM. Some of the existing research focuses on the development of knowledge bases via ontologies [132]. These can be uploaded online, made public, and subsequently customized by other users. These knowledge bases find wide application in those fields less covered by BIM schemas and file formats, such as Heritage BIM (BIM applied to architectures with cultural–historical character) [133]. Furthermore, the use of semantic technologies is widely applied by BIM researchers to optimize data transmission and sharing, sometimes circumventing the limitations of available formats such as IFC [134]. Guerra de Oliveira et al., in 2022, published a paper addressing these last two topics, by developing an ontology for architectural H-BIM in order to enhance the semantics of an algorithmically designed model [135].

Another work using semantic technology to extend the IFC standard is that of Wang et al. [136], which concerns the field of facilities management by means of sensors and Internet of Things systems. Other researchers, such as Rampini and Re Cecconi in 2023, proposed the use of synthetic images, alongside real ones, generated from 3D BIM models; this proposal aimed to improve the performance of training object detection models in facilities management [137]. Semantic technologies are very useful in the field of facilities management; in 2022, Chen et al. [138] developed a method to automatically detect defects in the concrete of buildings by exploiting aerial images and semantic-rich BIM models. Another example of semantic technology use is that of Oti-Sarpong et al. [139], who in their 2022 paper proposed a novel algorithm for querying online BIM libraries, using the items' attributes and not only their geometrical similarity or matching keywords. The Scan-to-BIM method can be seen as a sub-method of reverse engineering, that is, the process of retrieving a building or infrastructural feature and then producing a representation of it. This is a common practice in H-BIM, both for architectural modeling [140,141] and for structural health modeling [142].

It is very important to clarify that a multiplicity of studies simultaneously cover many of the topics already addressed. In the case of Banfi et al. [143], for example, the authors focused on a specific case study, the Claudian Aqueduct in the Appian Way Archaeological Park, integrating the geometric survey techniques of laser scanning and photogrammetry, knowledge of ancient Roman construction techniques and materials, semantic technology, HBIM, and extended reality (XR).

5.2.4. BIM-GIS

Another tool at the core of infrastructure's digitalization is GIS (the geographical information system). A basic requirement of a project is geographical coordination, and BIM is no different [144]. Research on GIS integration within BIM has produced many results. First of all, there is an existing field of research field GIS and BIM file formats' conversion to permit the integration of the two [145]. Other researchers have focused on specific applications, such as Mignard and Nicolle in 2014, who used BIM, GIS, and ontologies in urban facilities management [146]. Kurwi et al. [147] applied a similar integration approach to the design of rail projects, while Barazzetti et al. [148] published a paper on a BIM-GIS approach for roads' detection and parametrization using point clouds. Other applications cover underground utility management systems, drainage systems for roads [149], and systems for heritage [150].

5.2.5. Analysis Based on BIM Data and Facilities Management

As previously mentioned, BIM is about information. Before being processed, information is data. A building information model relies on a huge amount of data concerning several dimensions, and new methods to deal with the computation burden must be applied [151]. Data and information are used for analysis and represent a rich meaningful resource that must be organized in a standardized manner to ensure communicability [152]. Data analysis and information retrieval within Open BIM is an existing research focus. Zhou et al., in 2020, published a paper on methods of 3D spatial data analysis for BIM, presenting an outstanding and comprehensive review [153]. Ramji et al., in 2020, dealt with using BIM for evaluation of the energy performance of buildings in the early stages of a project, performing a data file format integration between BIM and BEM (building energy modeling) [154]. BEM is a thriving research topic, with great focus on energy efficiency evaluation, planning, and optimization [155–159]. For example, Bughio et al. [160] investigated potential reductions in indoor temperatures by exploiting simulations run in building information models. Data and information within BIM cover fields such as risk analysis [161,162], delay analysis [163], fire risk evaluation and management [164], and construction management in a broader sense [165–167]. Indeed, integrating other techniques within Open BIM, such as life cycle management and assessment, cost-estimating approaches, and scheduling systems, is a powerful tool within facilities management [168–172]. The applications that BIM data can provide in terms of data analysis are many and varied. For example, Nik-Bakht et al., in 2021, investigated the possibility of analyzing the acoustics of buildings by means of data stored in building information models, with specific reference to reverberation time [173]. Chen and Huang, in 2015, developed an emergency response model during construction fires based on the analysis of data from BIM models using evacuation route optimization systems [174]. Dols et al. [175] used BIM for road safety analysis by developing several different driving simulation scenarios. It can also be found that structural engineering benefits from BIM data analysis in terms of structural material degradation and damage management [176,177]. Moreover, other works, such as that of D'Amico et al. [178], have investigated the integration of non-destructive survey data into preliminary phases of digital design within BIM, with possible applications in pavement management systems for roads. Others have investigated the possible benefits of using the Open BIM methodology in renovation projects by developing an innovative approach named Living-Labs, which involves key stakeholders through consultations [179].

5.2.6. Digital Twins

Another recursive concept in research on Open I-BIM is what is referred to with the keywords 'digital twin'. Pregnolato et al. [180] consider it a means of introducing Civil Engineering 4.0 to existing infrastructures. In particular, the authors proposed a step-by-step workflow for producing digital twins of existing bridge infrastructures, while Lee et al. [181] and Kaewunruen et al. [171], working with the same aim, dealt with underground tunnels and subways stations. DTs are a tool for the constant supervision of buildings or infrastructure, the monitoring of health assessment parameters, and real-time maintenance planning, with a view to reducing the polluting impact of such operations [182,183]. Pollution reduction and sustainability levels' enhancement are some of the objectives of the Lazio Region (Italy) project for port areas' transformation into a ZED (zero-energy district). Agostinelli et al. [184] exploited the DT of the Anzio harbor, integrating BIM and GIS to assess energy efficiency measures.

5.2.7. BIM/Blockchain/IOT

Connected to the concept of digital twins is the IoT, which is a network of physical objects, i.e., 'things', that have sensors, software, and other technologies integrated for the purpose of connecting and exchanging data with other devices and systems on the

Internet. The IoT can be used to ensure that BIM information is updated in real time [185], particularly for the purpose of facilities management and maintenance [186]. The IoT can be used for real-time prediction of flooding; Edmondson et al. [187] designed a prototype Smart Sewer Asset Information Model (SSAIM9) for an existing sewerage network, developed using IFC4 and involving the use of IoT sensors for real-time monitoring and asset performance management.

The quantity and quality of data potentially contained in BIMs is such that the information that can be derived from them may be sensitive. This means that data defense systems are needed that are equal to the technical and economic importance of the projects that BIM addresses. One example of this is the Blockchain, a computer system based on nodes and components that uniquely and securely manages a public ledger consisting of a series of data and information, such as transactions, in an open and distributed manner, without the need for central control and with a near-zero probability of cracking. This has wide application potential within BIM and the AECO fields for the management of large projects [188–191].

5.2.8. Modeling/Design Methodologies

BIM involves a type of parameter modeling known as procedural parametric modeling, whereby modelled objects are linked through parametric relationships. Clearly, anyone working in BIM and BIM research is working in parametric environments and with parameterized models, thereby justifying the work of authors such as Biancardo et al. [192] and Zhang et al. [193], who have investigated the methodology's potential for practical applications in road engineering, and in geotechnical and dam engineering.

Other studies have focused on integrating BIM and its open approach into other methods and techniques that improve productivity, for example, 3D printing and pre-assembled or prefabricated buildings [194]. Schwabe et al., in 2019, proposed model-based rule checking for the planning of construction site layouts [195]. Some of the existing research focuses on the creation of specific BIM object libraries; for example, Bridge and Carnemolla [196] addressed the gap in BIM object libraries for facilitating social inclusion with sustainable architecture. Similarly, Xue et al., in 2018, published a paper proposing a segmentation-free derivative-free optimization (DFO) approach that would transpose the generation of as-built BIMs from 2D images into an optimization problem of fitting BIM components to comply with architectural and topological constraints [197]. Doukari and Greenwood's paper from 2020 presents an innovative approach for creating BIM directly from plan drawings using automatically derived parameters [198]. As multidisciplinarity is a key feature of the Open BIM methodology, some researchers have focused on the integration of architectural and structural modeling. Hamidavi et al. [199] developed a structural design optimization (SDO) prototype to semi-automate the structural design processes of tall buildings, residential buildings, bridges, truss, girders, etc., in their early stages.

5.2.9. Knowledge Transfer

Some existing research also focuses on knowledge transfer [200,201]. Indeed, one of the main obstacles to BIM's adoption in small- and medium-sized companies is the need to adopt a new production paradigm that involves the education of employees; this is costly both in terms of the money and time spent on education courses [202]. However, new technologies, digitalization, and new methodologies have always been economic drivers, and managers must confront this [203]. Finally, there are many works by those who have attempted to give a systematic order to the knowledge inherent in Open BIM and its applications, in construction [204], road infrastructure [205], and transport infrastructure hubs [206]. The attempt by Godager et al. [207] to formalize and systematize the concept of Enterprise BIM, i.e., a comprehensive and holistic way of utilizing BIM throughout a building's life cycle, is interesting; the authors made this attempt through harnessing the intersection of the technologies described above, such as IoT and AI, and integrating them with multidisciplinary methodologies such as life cycle assessment, aiming to optimize resources, minimize environmental impact, and improve safety in the context of the entire infrastructure life cycle.

5.3. Transport Infrastructures

5.3.1. Bridges

Academic research concerning bridges within Open BIM is in full swing; structural design, optimization, inspection, data retrieval and analysis are all hot topics [208]. The Open I-BIM approach has proved particularly suitable for structural health monitoring operations regarding both pillars, girders, and decks [209]. Artus et al., in 2022, published a study focusing on a BIM-based framework used to incorporate automatic bridge damage data acquisition and transfer, as a tool for inspectors to use in subsequent analysis and simulations [210]. However, BIM tools are also and above all the prerogative of design operations; in 2021, Girardet and Boton developed an algorithm for the automated production of a building information model of bridges based on structural design and data analysis [211]. Automation is one of the goals that researchers pursue, with the aim of reducing the time taken by certain BIM processes that are vital, but also time-consuming and prone to error. In 2020, Lee et al. published an innovative framework for automatic bridge design parameter extractions from point cloud data, with optimal results and only a 0.8% error in parameter estimation [212]. Other authors have instead embraced the idea of Open BIM as a management tool for various phases of a bridge's life, using terrestrial laser scanning technology for the retrieval of geometric data as the basis for a BrIM process (as a sub-entity of BIM), and integrating this methodology with a decision support system for asset management [213].

5.3.2. Tunnels

Regarding tunnel infrastructure, Massimo-Kaiser et al. [214] evaluated how the use of BIM has affected the social and economic aspects of seven different tunnelling projects, resulting in a general benefit. The studies of Wang et al. [215] focused on sustainability. In particular, the authors designed a tunnel using parametric modeling in a visual programming software environment (Dynamo), which allowed them to enhance the geometrical modeling and to perform a carbon emission assessment; thus, the tunnel design could be positively affected by the parameter of sustainability. Yu et al. [216] formulated methods of configuring BIM + VR prototypes to enable the visualization of the physical context of tunnels to enhance emergency response training, in particular regarding fire risks. Borrmann et al. [217] developed a sophisticated framework for the multi-scale geometric–semantic modeling of shield tunnels in subway transport systems, for BIM and GIS applications. The authors placed particular emphasis on providing consistency in representations across the different levels of detail (LoDs), and they proposed a potential extension of IFC for incorporating multi-scale representations of shield tunnels in a manner that enables the automatic and consistent updating of all dependencies on finer levels when an object is modified on a more coarse level. Additionally, Zhou et al.'s paper from 2018 looked at the modification and enhancement of IFC standards for shield tunnels, a common approach for subway tunnel excavation that is not yet properly represented by IFC [218].

5.3.3. Roads

There are many and diverse applications of Open BIM to road infrastructure. Some authors have focused on the management and maintenance of existing assets, others seek to innovate design processes, and still others search for solutions to specific problems and design contexts. Vignali et al. [219] embarked on designing a new road intersecting an existing road and a railway line, evaluating how the use of BIM in a complex context benefitted the design solution. Tang et al. [220] used an advanced visual programming language environment to integrate pavement structure analysis into 3D road design within BIM. With a similar approach, Oreto et al., in 2021, performed a decay analysis on a road pavement based on material and mixtures data, and developed a management tool for scheduling urban road maintenance [221]. In the context of maintenance and asset information management, Aziz et al. [222] worked on integrating big data, sensors, and BIM for highway applications, while Kim et al. [223] developed a BIM approach based on smart objects, from which information about scheduling and cost estimations could be automatically derived. A specific design problem for highways concerns underpass road clearance in road-widening projects; in 2022, Jiang et al. published their paper proposing a method for building road digital twins from online map data, and a method for road widening based on them [224].

Another important aspect of road infrastructure is traffic control and sensor systems, such as intelligent transport systems (ITS). Mirboland and Smarsly, in 2021, proposed an extension of IFC for modeling and semantically described an ITS for highways [225]. Moving away from motorways toward micro-mobility, in 2020, Campisi et al. dealt with cycling paths using I-BIM to connect cost and safety requirements in the planning phase, developing a methodology which, starting from the identification of the intervention area and the available economic resources, provides all the elements for designing a cycling path, from location and safety to the definition of preferred options in terms of materials [226]. Biancardo et al. [227] proposed a BIM workflow for modeling airport terminal expansions, demonstrating a reduction in construction times and costs for their case study, which was based on the ‘IV Bridge’ project for the expansion of the departure area of Naples Capodichino International Airport by means of an elevated walkway.

5.3.4. Railways

As far as railways are concerned, there are several studies testing the suitability of Open I-BIM for the planning, design, operation, and maintenance of railway works. Park et al. [228] focused on reverse engineering a ballasted track of a straight railway stretch. The authors focused on methods for automatizing onerous and error-prone manual operations such as point cloud denoising and registration and 3D modeling, within BIM-based tools. Moreover, the railway ballast representative parameters were selected for automating maintenance planning. Similarly, Grandio et al. [229] focused on automation of the segmentation operations of point clouds representative of extended railway complexes by exploiting deep learning. Acerra et al. [230] investigated the potential of the Open I-BIM approach for the design of an urban tramway line, and clash detection simulations and scheduling analyses were performed. In 2019, Neves et al. published a paper on a case study of rail track rehabilitation based on the implementation of BIM with a comprehensive workflow [231]. Part of the research focused on the use and expansion of the IFC standard to include the description of railways, which certainly favored and supported the development of the IFC 4.3 standard, which can now also describe railway objects [232–234]. An interesting example of applying Open BIM to asset management can be found in the work of Ciccone et al. [235]. The authors had the main goal of systematizing information by digitalizing the infrastructure of the Cancello–Benevento railway line in Italy in order to assess possible performance gaps within the national railway standards. A federated digital model was developed for the survey, data management, maintenance, financial evaluation, and general asset management, through software specifically designed and based on the IFC4×2 schema. Seo and Lee [236] focused instead on developing suitable BIM libraries of railway objects complying with South Korean standards. Haussler et al., in 2021, dealt with code compliance checking for railways in Germany by using a visual programming language environment and integrating BIM, BPMN (business process model and notation) and DMN (decision model and notation), thus investigating rather the railway BIM models released in IFC format would provide all the required information or not [237].

5.3.5. BIM Authoring

Santamaria-Pena et al., in their 2022 paper, provide an example of a workflow using Autodesk products, in particular Revit and Civil 3D, for modeling levelling, embankments, and overburdens [238]. In 2021, Fabozzi et al. published their work on a BIM-based approach to the geotechnical and numerical modeling of conventional tunnel excavation using Bentley products [239]. Additionally, in the work of Biancardo et al. (2021), Bentley software was involved in the as-built modeling of an existing railway line in Croatia. Works such as that of Abbondati et al. [240] and Guerra De Oliveira et al. [241] have investigated the applicability of I-BIM to airport infrastructure management, and in particular to runway pavement maintenance. Yin et al. [242] dealt with tunnels. Port infrastructure has also been the subject of academic interest; Hua et al. (2020) applied BIM technology to the design of breakwaters [243], while Xiao et al. [244] focused their work on canals.

Usually, software for the geometric modeling of roads is based on the realization of three-dimensional axes, with which a geometry (the cross-section) is associated, and which will be extruded along to obtain the road solid. However, this entails certain limitations, especially concerning those more elaborate objects that nevertheless constitute fundamental parts of the infrastructure, such as safety barriers, hydraulic works, technological installations, furnishing elements, etc. Some academic works focus on the compensation of parametric object libraries referred to for modeling, which are often not sufficiently provided; this is the case with the work of Biancardo et al. (2020), for modeling retaining walls and safety barriers [40]. In some academic work, I-BIM has been applied to the modeling of existing roads to obtain an information model of the condition of a road’s pavement, in order to support the management of the road pavement itself [245]. As expected, I-BIM has many applications for pavement management. Indeed, the information-rich digital model obtained by applying the I-BIM methodology is a tool able to support the development of road pavement maintenance systems, both in urban and suburban areas. In the case of Oreto et al.’s work, the authors integrated methods such as life cycle assessment for technical–economic assessments and maintenance planning into the I-BIM methodological framework [246].

An example of the application of BIM in this field can be found in the work of Biancardo et al., 2021, in which an as-built model of a main street in the historic center of Naples (Italy) was produced by combining several software tools and using advanced surveying techniques, such as laser scanning and photogrammetry, resulting in a case study of road H-BIM [247]. Other cases of BIM applied to roads made of stone led to Archaeo-BIM; these are located in the archaeological park of Pompeii [248,249]. In conclusion, the academic community is well aware of the potential of the BIM methodology applied to the road environment. The number of case studies is growing. The main obstacle to wider dissemination is related to software development. This can be improved, particularly with regard to two aspects: modeling, which for higher levels of detail becomes more difficult and less automatic (and therefore, generally more expensive), and interoperability.

This last point is closely linked to the development of IFC. BuildingSMART is currently working on improving the IFC version 4, while IFC 5 is already in the planning stage. As reported on the BuildingSMART official website www.buildingsmart.com (accessed on 23 May 2023), these formats will include semantic representations of horizontal infrastructure elements (bridges, tunnels, railways, and roads).

6. Discussion

Within this literature review, the improvements that the Open I-BIM approach brings to the civil engineering industry can be seen in high-quality projects carried out with fewer resources. In general, optimized results are achieved. Indeed, the collaborative and technological nature of the methodology allows all design, economic, financial, and environmental requirements, as well as both technical and regulatory constraints, to be taken into account simultaneously.

This means that design is no longer divided into stages according to watertight compartments, but is transformed into a holistic, multidisciplinary approach, which considers the most diverse instances converging towards an optimal solution. This greatly limits the need to return to the project during the construction phase, i.e., to make variants, and thus avoids extra costs. In fact, design changes made during construction are responsible for the highest costs and the worst results in terms of quality. Furthermore, it favors the involvement of stakeholders in the planning phase, and avoids future slow-downs due to poor public acceptance of the project.

In addition, the data contained in the digital models allow for more efficient management of project information, improving many aspects including bureaucratic time scales, documentary deliveries relating to the progress of works, verification of the quality of materials, and conformity of equipment and tools, administrative fulfilments, etc. Finally, all of these factors also have a clear impact on safety at work.

BIM applied in an open manner to infrastructure (Open I-BIM) is already a reality in the industry, especially for large-scale projects.

Bridges are among the works wherein Open I-BIM is most effective; some good examples are the San Giorgio bridge in Genova, Italy, designed by the starchitect Renzo Piano and built using BIM authoring tools from Bentley software house (these tools prompted a considerable speeding up of the work) [250,251], and the Ovalo Monitor Bridge in Peru, which is a very complex project aided by the parametric modeling capabilities of Open I-BIM, the cloud-based data environment that allowed for the identification of interferences and incompatibilities, and better scheduling and general coordination [252]. The railway sector also benefits from the application of Open I-BIM. One example, back in Italy, is the high-speed station at Afragola, designed by starchitect Zaha Hadid as an interchange between the existing Rome–Naples line and the Naples–Bari line currently being planned and built [253,254]. Another good example is the Sound Transit Operations and Maintenance Facility in Seattle, USA, which includes light rail, commuter rail, a bus transit program, and more [255].

Other applications include environmental engineering plants such as the Durleigh Water Treatment Works, Somerset, UK, which received a major upgrade based on Open I-BIM for the calculation of the structure's operability and for clash detection [256], and the Pierrefonds Waste Management Plant in France, wherein the Open I-BIM approach enabled proper coordination and model sharing between the engineering teams, and was crucial to the project [257].

Additionally, airports' infrastructures benefit from the Open I-BIM methodology. This is the case for Oakland International Airport [258] and Helsinki Airport [259].

Yet, there are many challenges associated with the implementation of Open I-BIM in the civil engineering sector, which align with the nature of the infrastructure to be modelled. Indeed, BIM was first developed for vertical architectures. Infrastructures such as roads, railways, airport runways, dams, bridges, etc. have such a linear characterization and extension that it is very complicated to model them according to the same schemes and principles as architectural BIM. For this reason, buildingSMART has had to invest a great deal of energy in updating the IFC representation standards that originated in the building/architectural field (IFC 2×3), only accomplishing barely adequate standards (IFC 4) in recent years. Other limiting factors relate to the complexity of the modelling software, for which practitioners have to train and keep up-to-date (this entails the investment of time, energy, and money on the part of both professionals and companies), and a general approach that is insufficient to capitalize on the potential benefits of BIM.

However, many are working to overcome the remaining limitations that hinder the full adoption of the Open I-BIM methodology. In particular, buildingSMART is further developing the IFC 4×3 format for the representation of roads (IFC Road) [260], railways (IFC Railway) [261], bridges (IFC Bridge) [262], ports, and waterways (IFC Ports and Waterways) [263]. In addition to the interoperability issue, another challenge is that of training people in conscious use of Open I-BIM so that they can fully exploit its potential. The academic and industrial worlds are actively collaborating to improve the workflows currently in use by integrating algorithms that automate the design phases, making the shift from traditional to Open I-BIM less onerous.

7. Conclusions

Discussion on the digitization of infrastructures is heated, and is fed by continuous speculation. In the sea of publications, scientific papers, legislative efforts, and corporate and entrepreneurial initiatives, clarity is needed to provide a knowledge base capable of systematizing concepts related to the more general methodology in use.

In this vein, this paper focuses on describing the state of the art in Open I-BIM to provide an up-to-date literature review consisting of studies published in the last decade (2013–2023). This review has shown that much work remains to be done in the field of Open BIM applied to infrastructure. It can be deduced that there is a need to deepen and develop the technological aspects of the respective topics of interoperability, performance methodologies, and applications for solving infrastructure-related case studies.

The existing research, considering its trends, shows an interest in investigating and increasing the knowledge, skills, and competences needed to exploit advances in BIM platforms, and to enhance the interoperability of applications, thereby avoiding data loss when exporting models in the open IFC format by improving the degree of compliance. Another aspect that we can infer from the existing works is the focus on automation for the electronic management of work processes, e.g., for point cloud processing and subsequent 3D modeling.

The research aim that will engage scholars in the coming years is the definition of common processes to achieve full implementation of the methodology. This implementation will involve different disciplines so that they can interact in the same digital environment, thereby fully realizing large-scale Open BIM, in which the infrastructure sector will be a key player.

Analyzing the trends, it is notable that many studies are deepening the development of interoperability formats that limit the loss of information during export. In this sense, there are high expectations for IFC4×3, a very important extension in the infrastructure sector, as it allows the export of track models, and road and rail modelers in IFC format. The limitations of this research paper are related both to the method of the literature review (which involved using keywords) and to the nature of the research topic itself. Indeed, our research activities have highlighted the use of the acronym I-BIM in various scientific disciplinary fields, in which different meanings are assigned to the 'I' in front of the word BIM. For example, scientific articles related to BIM-I emerged in the results. This is an acronym used to identify BIM-1 and the related compounds BIM-2, BIM-3 and BIM-8, which are bisindolylmaleimide-based protein kinase C inhibitors. Considering that the 'I' is not uniquely understood as 'infrastructure', it was necessary to perform a manual check on several occasions, in addition to the application of the subject area filter in Scopus during the publication selection process.

Another problem has arisen in that many authors consider the topic without referring to it as Open I-BIM; many do not use the "I" in the acronym, or they do not use the word "open", etc. Obviously, mismatches in writing (i.e., other keywords instead of Open I-BIM) excludes texts using "Open Infrastructure BIM" from the search filters applied for this review, which was performed using Scopus. In order to remedy the fact that significant scientific publications have been excluded for reasons of form and not concept, it was necessary to carry out a second identification step in order to encompass all the relevant studies and to overcome the issue of different keywords. Another identified shortcoming is to be found in the multidisciplinary nature of the subject matter, which made it complicated to split and, consequently, to treat the categories of interoperability, methodology and transport infrastructures separately. By their nature, these categories include studies involving research branches because they are interconnected. An examination of the current state of publications on Open I-BIM outlines future research directions. This research work represents a pioneering study for the systematization of knowledge on the topic of

Open I-BIM. Based on the results described, this study may lay the foundations for interested researchers, determined to broaden their knowledge horizons, to build upon.

To sum up, this research work makes a significant contribution to the systematization of knowledge on the topic of Open I-BIM, identifying the state of the art, research trends, reporting a critical analysis of the scientific literature reviewed, and aspiring to form a basis for more and more innovative insights.

Based on the methodological approach of this research, analysis should be extended to other Open I-BIM-related topics in the future, for example, the development of the IFC format and the development of other and innovative techniques for workflow automation. We must also keenly follow the evolution of the relationship between this methodology and new technologies; advances in artificial intelligence, for example, will present a new project-assisted approach, the implications of which are not yet well defined, nor the characteristics of its relationship with established methodologies such as Open I-BIM.

Author Contributions: Conceptualization, A.S. and S.A.B.; methodology, M.N. and G.D.; software, M.I. and C.M.; validation, M.N. and G.D.; formal analysis, A.S. and S.A.B.; data curation, M.I. and C.M.; writing—original draft preparation, M.I. and C.M.; writing—review and editing, A.S. and S.A.B.; visualization, M.I and C.M.; supervision, A.S. and S.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

Acronym/Abbreviation	Explanation
I-BIM	Infrastructure building information modeling
DT	Digital twin
H-BIM	Heritage building information modeling
IoT	Internet of Things
IFC	Industry Foundation Classes
LCSA	Life cycle sustainability assessment
MOBs	Multi-owned buildings
BRMS	Business rule management system
VR	Virtual reality
AR	Augmented reality
MR	Mixed reality
XR	Extended reality
SHM	Structural health monitoring
COBie	Construction Operations Buildings information exchange
AI	Artificial intelligence
MVCNN	Multi-view convolutional neural network
UAV	Unmanned aerial vehicles
GIS	Geographical information system
BEM	Building energy modeling
ZED	Zero-energy district
AECO	Architecture engineering construction operation
DFO	Derivative-free optimization
SDO	Structural design optimization
BrIM	Bridge information modeling
LoD	Level of detail
BPMN	Business process model and notation
DMN	Decision model and notation
Archaeo-BIM	Archaeological BIM

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