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KNOWLEDGE DISSEMINATION TRAJECTORY OF BIM IN CONSTRUCTION ENGINEERING APPLICATIONS

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Abstract. In recent years, the construction industry worldwide has shown significant interest in Building Information Modeling (BIM). This study aims to analyze the dissemination of knowledge about BIM in construction engineering applications using Main Path Analysis (MPA). The research sample comprises 3,761 papers related to BIM's application in the construction industry, sourced from the ISI Web of Science database. Initially, we investigate trends in paper publications, conduct country and journal analyses, and examine author statistics. Subsequently, we calculate traversal counts along the search path links to reveal the development trajectory of BIM. The trajectory of BIM's evolution in the construction industry can be divided into four stages as identified through the global key-route main path analysis: 1) BIM standardization; 2) Integration of completed building projects using BIM; 3) BIM applications in precast construction projects; and 4) BIM applications in land management. These findings provide a clear understanding of how BIM has been applied and evolved within the construction industry.

Keywords: building information modeling (BIM), main path analysis, citation network, trajectory analysis.

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1. Introduction

Building Information Modeling (BIM) has its roots in the expansion of the Building Description System (BDS), initially proposed by Charles Eastman in 1974–1975 (Eastman, 1975). The term "BIM" was initially coined and employed by the software corporation Autodesk to characterize and promote a range of architecture, engineering, and construction (AEC) software tools, such as Revit. Scholars, decades ago, harnessed the information technology capabilities offered by companies like Autodesk, Bentley Systems Software, and Graphisoft to introduce BIM to the world. The adoption of BIM modeling has ushered in a transformative era for the construction industry. BIM models have revolutionized how the construction sector functions. They enable the seamless sharing, creation, addition, updating, searching, retrieval, transmission, and exchange of both geometric and non-geometric data throughout a building's entire lifecycle, spanning planning, design, construction, operation and maintenance, and eventual demolition.

In recent times, BIM has emerged as a focal point of interest within the global construction industry. This has led to rapid and extensive progress in the development of BIM applications for construction, necessitating a continuous awareness of technological advancements, knowledge dissemination, and emerging trends in this domain. Most prior studies in the existing literature have concentrated on the evolution of BIM applications for specific technologies, such as three-dimensional (3D) spatial data analytics (Zhou et al., 2020), semantic enrichment (Dinis et al., 2021), and multi-criteria decision making (Tan et al., 2021). Occasionally, subjective opinions of authors have been introduced into these studies. The process of gathering information from background analysis, journal publications, and self-referential literature can be excessively time-consuming, often resulting in an unclear or incomplete depiction of developments and citation relationships. To effectively manage the potential deluge of information that could

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diversify the benefits derived from BIM applications, examining the developmental trajectory of BIM applications emerges as a viable solution.

The objective of the study is to discern the knowledge dissemination path of BIM within the context of construction engineering applications using Main Path Analysis (MPA). MPA serves as a methodology to delineate the trajectory of predominant thought patterns within a particular subject area by scrutinizing references in the literature, thereby tracking the progression of that subject or technology. During the analysis, the intricate web of citations is simplified to highlight only the pivotal pieces of evidence. Nevertheless, there are certain limitations associated with this study. Firstly, the dataset exclusively comprises journal articles. Secondly, it does not encompass several essential BIM publications and documents, including the BIM Guides (General Services Administration [GSA], 2017), IFC Implementation Guides, and the BIM Handbook issued by the General Services Administration (GSA) of the United States Federal Government (Sacks et al., 2018).

2. Literature review

2.1. Citation analysis

A citation denotes an entry within a list of references or texts cited within the context of academic research. It establishes a clear connection between texts that share a common perspective or viewpoint. Assessing the relevance of cited literature involves examining the interplay between the citation list and the literature it references. Baird and Oppenheim (1994) contended that citation analysis holds the potential to unveil emerging disciplines, popular subjects, the historical development of a topic, and pivotal moments in its evolution. Consequently, it occupies a significant realm within bibliometrics and information science. The scientific methodologies applied in disciplines such as mathematics, statistics, and logical analysis can be adapted to compare, synthesize, and comprehend the dynamics of citing and being cited within research papers and academic journals. Authors employ these methods to delve into the quantitative attributes and intrinsic value of citations. Hirsch (2005) introduced the h-index as a metric, defined as the count of papers with citations equal to or exceeding the value of h. Citation relationships offer insights into the extent to which individual research has contributed to a specific field. Moreover, the h-index serves as a tool not only for evaluating individual contributions but also for gauging the influence of academic journals within their respective fields of research (Bornmann & Daniel, 2005; Mingers, 2009; Saad, 2010).

2.2. Applications for research trajectory

MPA significantly facilitates the comprehension of the technical evolution of BIM in construction applications. Initially introduced by Hummon and Dereian in 1989, MPA serves as a powerful tool for uncovering the predominant flow of knowledge within a particular scientific or technological field, drawing insights from citations within academic or proprietary literature. While tracing the flow of knowledge in a small citation network may not pose significant challenges, the complexity escalates considerably in larger networks. For substantial citation networks, a simplified focus on the main paths is often recommended (Hummon & Dereian, 1989). A citation network is established by creating links between all referenced documents in pairs. Within this citation network, a source node represents a work that is cited but doesn't itself cite other works, signifying its role as the origin of knowledge. A sink node represents a text that is cited as a source of knowledge but does not quote other texts, marking it as the endpoint of knowledge dissemination. MPA systematically identifies all potential routes from source to sink in a citation network. It computes traversal counts (or weights) between pairs of nodes and subsequently connects the links with higher traversal counts to establish the main path (Verspagen, 2007). Essentially, MPA serves as a method for tracking the flow of predominant ideas within a specific subject area by scrutinizing citation relationships among studies in the literature. This approach proves valuable in comprehending trends in the evolution of the subject or technology (Nooy et al., 2005).

According to Liu and Lu (2012), employing MPA in the analysis of citation networks offers three distinct advantages. Firstly, it simplifies intricate citation networks into a concise and representative set of nodes and connections. Secondly, it highlights the primary advancements within the field, serving as a clear introduction for newcomers to the subject. Thirdly, it pinpoints pivotal milestones in the historical development of a specific field. The significance of tracing these main paths lies in their ability to illuminate the essential evolution of a subject or technology throughout its progression. These main paths of development can be discerned within the broader context of the subject or technology's overall evolution, facilitating subsequent generations' rapid and accurate comprehension of the principal developmental trends when delving into that subject or technology.

When pursuing the identification of the main path, it becomes crucial to assess the significance of each link within the network. The importance of these links is typically gauged by calculating the number of traversal counts passing through each link. Verspagen (2007) delineated MPA into two steps: the computation of traversal counts and the tracing of paths. In the first step, an algorithm is employed to compute traversal counts, with distinct weights assigned to individual links within the citation network based on the perceived importance of the relationships between preceding and subsequent citations in the literature. Several commonly used algorithms include SPC (search path count), SPLC (search path link count), SPNP (search path node pair), and NPPC (node pair projection count) methods. SPC adheres to Kirchhoff's node law, where the sum of inflow traversal weights equals that of outflow traversal weights. However, knowledge dissemination in the scientific and technological realm operates differently than the SPC analogy, as intermediates also contribute to generating knowledge.

The SPLC analogy considers intermediates not only as carriers of knowledge but also as origins of knowledge. In contrast, SPNP goes further, suggesting that intermediates serve as knowledge repositories, which is not aligned with the actual scenario. Consequently, among these three methods, the SPLC analogy aligns most closely with the dynamics of knowledge diffusion observed in the development of science and technology. Therefore, the SPLC calculation method was employed in this study.

3. Data collection and basic analysis

3.1. Assumptions and limitations for data collection

In this study, data underwent filtration through the advanced search feature provided by the ISI Web of Science (WOS) database. Both the Science Citation Index Expanded (SCI-EXPANDED) – spanning from 2000 to 2020 – and the Social Sciences Citation Index (SSCI) – covering the years 2000 to 2020 – were queried, encompassing all languages and document types. The search string comprised keyword groups as follows: "BIM" or "building information model*". The search condition was defined as "(TS = ("BIM" or "building information model*") OR TI = ("BIM" or "building information model*")) AND TS = (construction OR civil engineering OR "building")". These keywords were employed to assemble a collection of academic papers pertaining to the application of BIM in construction projects, which will be explored in this study. The literature sources used in this study were obtained from the WOS database. WOS is a web-based citation indexing system established by Thomson Reuters in 1997, including the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Conference Proceedings Index – Science (CPI-S). The literature covers a wide range of disciplines, including science, engineering, medicine, agriculture, the humanities and social sciences, and can be searched across disciplines and databases for information such as bibliographies, authors, abstracts, and citations.

3.2. Keyword search and data collection processes

Throughout the search process, a significant portion of the located papers primarily centered on the developmental aspects of BIM within the realm of construction engineering. These papers were excluded due to their limited relevance to our present research focus, and their inclusion had the potential to introduce biases into the results of the MPA. In total, 144 papers fell into this category. Another challenge was the inability to cite certain seminal early papers on BIM because they primarily pertained to parametric 3D modeling techniques. Charles M. Eastman, often credited as the pioneer of BIM, conceptualized this approach as far back as the late 1970s. However, the practical application of this technology within the construction industry has only gained prominence relatively recently, making it impractical to incorporate these early works into our citations.

Subsequently, the term "BIM" was embraced by the software giant Autodesk as part of their strategy to promote their AEC software tools. This move played a pivotal role in laying the initial groundwork for the utilization and advancement of BIM within the field of construction engineering. It's crucial not to underestimate the significance of this body of literature when discussing the progression of BIM applications in construction engineering. To ensure a comprehensive search process and minimize the risk of omitting relevant materials, a second search was conducted. In this second search, we included the keyword group "building model". The search criteria were defined as follows: "(TS = ("BIM" or "building information model*" or "building model*") OR TI = ("BIM" or "building information model*" or "building model*")) AND TS = (construction OR civil engineering OR "building")". However, this approach resulted in an excessive number of retrieved papers, with many of them being unrelated to the study's topic. To address this issue, we conducted a data cleaning process to remove irrelevant data that were not referenced in the literature. After this cleanup, we identified a total of 3,761 papers relevant to the application of BIM in construction engineering, which were selected as the sample for this study.

3.3. Basic analysis

Trend of growth in the number of articles

A total of 3,761 articles pertaining to BIM within the construction domain were located within the WOS database, as indicated by the fundamental literature count statistics displayed in Figure 1. The period from 2000 to 2010 witnessed a gradual growth in literature concerning BIM's application in the construction sector. In stark contrast,

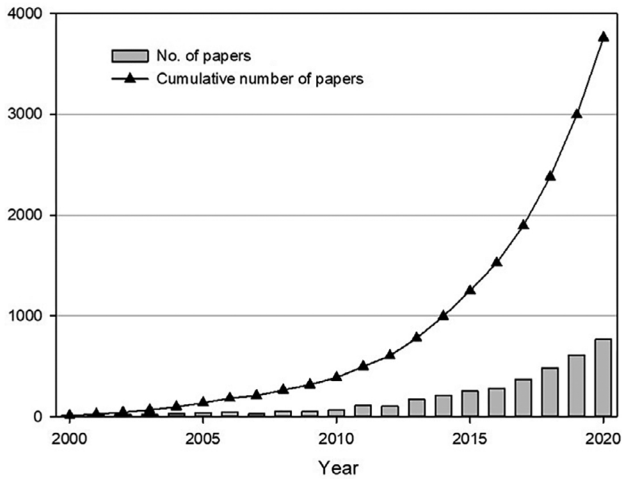

Figure 1. Growth trend of the number of papers

the subsequent decade, spanning from 2011 to 2020, experienced a substantial surge in literature focused on BIM within the construction field. These data unequivocally affirm the ongoing year-over-year expansion of global research activities in the realm of BIM.

Country/region analysis

This study has determined the leading ten countries or regions based on research contributions in the field of applying BIM in construction engineering, contributed by scholars from various parts of the world. As depicted in Table 1, China secured the top spot with 809 articles, followed closely by the United States in second place with 559 articles. South Korea held the third position with 258 articles, while Taiwan ranked tenth with 113 articles. These top ten countries or regions collectively contributed to 70.5% of the total number of research papers in this area.

Table 1. Top ten countries in terms of citations in the BIM literature

Rank	Countries	No. of Patents	% of 3,761
1	People's Republic of China	806	21.4%
2	United States of America	556	14.8%
3	South Korea	257	6.8%
4	England	204	5.4%
5	Germany	186	4.9%
6	Australia	153	4.1%
7	Canada	136	3.6%
8	Spain	127	3.4%
9	Italy	117	3.1%
10	Taiwan	113	3.0%

Journal statistics

Within the realm of research related to the BIM application in construction engineering, there exist several academic journals of particular significance. Table 2 presents a compilation of six academic journals that have published over 100 papers on this topic within the last two decades. Topping the list in terms of the sheer number of publications is *Automation in Construction*, which has disseminated 545 articles. Following closely are the second to sixth-ranked journals, namely *Energy and Buildings*, *Sustainability*, *Advanced Engineering Informatics*, *Journal of Construction Engineering and Management*, and *Journal of Computing in Civil Engineering*, in that respective order.

Author statistics

The study employs the h-index as a metric to pinpoint the authors who have left a substantial impact and made significant contributions to research in the domain of BIM within construction engineering. Initially, authors were ranked based on their h-index, and in the event of a tie, their ranking was further determined by the number of articles where they served as the first author. Table 3 showcases the top twenty authors according to these criteria. Notably, the five most influential authors, in descending order, are Sacks, Wang, Cheng, Eastman, and Love.

Table 2. Top twenty academic journals for research on the application of BIM in construction engineering

Rank	Journal	No. of Papers	g-index	h-index	Years Active
1	Automation In Construction	545	115	76	2000~2020
2	Energy and Buildings	164	67	40	2002~2020
3	Advanced Engineering Informatics	116	54	33	2004~2020
4	Building and Environment	87	50	30	2002~2020
5	Journal of Construction Engineering and Management	104	45	25	2005~2020
6	Journal of Wind Engineering and Industrial Aerodynamics	80	43	24	2000~2020
7	ISPRS Journal of Photogrammetry and Remote Sensing	48	43	22	2002~2020
8	Applied Energy	48	39	26	2012~2020
9	Journal of Computing in Civil Engineering	103	37	24	2005~2020
10	Journal of Management in Engineering	50	33	23	2009~2020
11	Journal of Cleaner Production	49	33	19	2015~2020
12	Earthquake Engineering & Structural Dynamics	29	29	20	2000~2020
13	Engineering Structures	39	28	16	2001~2020
14	Remote Sensing	66	24	16	2013~2020
15	Journal of Building Engineering	54	24	15	2016~2020
16	Engineering Construction and Architectural Management	82	23	16	2015~2020
17	Sustainable Cities and Society	34	23	15	2011~2020
18	Energy	23	23	14	2000~2020
19	Sensors	40	23	11	2008~2020
20	ISPRS International Journal of Geo-Information	70	22	13	2012~2020

Table 3. Top twenty authors in terms of research impact in the field of BIM in construction applications

Rank	Authors	g-index	h-index	Years Active	Total Number of Papers in the Field	Total Number of 1st Author Papers	Country/ Region	Appears in Main Path
1	Wang, XY	39	21	2010–2020	39	2	Australia	
2	Sacks, R	34	23	2004–2020	34	10	Israel	Y
3	Cheng, JCP	33	19	2013–2020	33	4	China	Y
4	Love, PED	26	15	2011–2020	26	11	Australia	
5	Li, H	26	14	2011–2020	42	3	China	
6	Eastman, CM	24	19	2004–2020	24	1	USA	Y
7	Lu, WS	23	14	2013–2020	25	6	China	
8	Lee, G	22	14	2004–2019	22	7	South Korea	Y
9	Wang, J	22	11	2014–2020	22	5	China	
10	Kim, H	21	14	2009–2020	29	13	South Korea	
11	Lee, S	21	11	2011–2020	22	10	South Korea	
12	Rezgui, Y	20	14	2011–2020	20	2	Wales	
13	Borrmann, A	20	11	2009–2020	21	5	Germany	Y
14	Kim, K	20	11	2011–2020	21	12	USA	
15	Tamura, Y	19	13	2001–2019	19	5	Japan	
16	Rajabifard, A	19	12	2014–2020	19	0	Australia	Y
17	Chen, K	19	11	2016–2020	19	5	China	
18	Lee, J	18	11	2010–2020	18	7	South Korea	
19	Xue, F	17	11	2016–2020	17	7	China	
20	Teizer, J	15	12	2010–2020	15	2	Germany	Y

4. Main path analysis and result analysis

4.1. Software and settings

This study employed both the Mainpath and Pajek software to analyze data derived from 3,761 research papers and their associated citations. To facilitate this analysis, we initially saved the data as text files, which were subsequently imported into the Mainpath software. Within the Mainpath software, we made selections regarding the primary path type and the methodology for calculating link weights in the analysis. It's important to note that the initial analysis often had to be halted due to the presence of citation loops within the citation network. The Pajek software, on the other hand, was specifically designed for the analysis and visualization of intricate and extensive networks. Apart from offering a variety of metrics for evaluating the network's structure and interconnectedness, Pajek also provides clustering tools to identify sets of nodes with shared attributes. Moreover, it features an MPA module that enables users to pinpoint groups of nodes exerting a notable influence on the historical trajectory within a time series.

These recurring loops encompassed various scenarios, including self-citation, instances of A citing B and B citing A, as well as more complex patterns such as A citing B, B citing C, and C citing A, and so forth. These loops were manually eliminated to ensure accurate analysis. To visualize the primary path within the BIM in construction papers, the ".paj" file must first be imported into the Pajek software. Subsequently, under the "Draw" menu, the "Draw Partitions" option should be selected. The software will then automatically arrange all the nodes along the main path in a circular configuration. To explore the relationships between these nodes, one can choose "Layout" → "Energy" → "Kamada-Kawai" → "Separate components" to open the main path diagram. For an insight into the link weights, users can access this information by selecting "Options" → "Lines" → "Mark Lines" → "with Values". To visualize these weights, one can further choose "Options" → "Lines" → "Different Widths", which will display the weights in various thicknesses and include directional arrows as needed.

4.2. MAP implementation

The SPLC calculation method has been employed in this study. This method involves selecting any link within the network and treating all nodes, including the endpoint of the link itself, as potential starting points. For each of these starting points, we calculate the number of feasible paths passing through the particular link. Simultaneously, we determine the number of feasible paths extending from the endpoint of the link to all sinks within the network. The SPLC value for the link is then derived by multiplying these two quantities together. A larger SPLC value signifies a higher volume of traversal counts for that link, indicating a more substantial impact of that linkage on the overall technological development of the field. To illustrate the calculation of the SPLC value, let's consider line EF in Figure 1 as an example.

There are five distinct points, namely A, B, C, D, and E, inclusive of the endpoint itself (E), that precede the termination of the link. Consequently, there exist five potential paths traversing this line, namely A-D-E-F, B-D-E-F, C-E-F, D-E-F, and E-F. Conversely, from the origin point (F) to each sink (represented by blue nodes, encompassing J, K, and L), there are three conceivable paths leading to each sink individually (F-H-J, F-G-K, and F-G-L). When we multiply these two quantities together (5 × 3 = 15), it yields an SPLC value of 15 for the EF segment. By systematically repeating this logical process, SPLC values for all interconnected lines can be calculated, as visually demonstrated in Figure 2. Subsequently, we can embark on the search for the primary path within the network.

The second step, known as path tracing, involves the computation of traversal counts (weights) for all lines within the citation network and subsequently tracing significant paths utilizing a specific method. Each path tracing method offers a distinct perspective, leading to different trajectory patterns based on these viewpoints. These path tracing techniques encompass the local main path, global main path, and key-route main path. It's essential to acknowledge that all original MPA methods come with their inherent limitations. This study has opted for the global key-route main path tracing method, as proposed by Liu and Lu (2012). This method compensates for the potential omission of important links within the local main path. In most instances, the global key-route main path encompasses both the local main path and the global main path. Within the global key-route main path, we identify the key route with the highest traversal count from the citation network. To fully grasp the comprehensive context of technological development, the main path is determined by extending forward from the beginning and backward from the end of the key route. By default, we set the number of key routes to ten, encompassing the top ten most significant links within the citation network. The two steps involved in this process are outlined below: Step 1: Establish the key routes by identifying the top ten traversal counts and designating them as key routes. Step 2: Overlay the paths: Extend each of these ten lines outwards and overlay the key paths to form a complete path. The global key-route main path is attained by superimposing these ten key-route segments, serving as the core structure of the citation network.

4.3. Results and discussion

To trace the trajectory of knowledge diffusion, the SPLC approach closely aligns with the knowledge diffusion scenarios observed in the development of science and technology (Liu et al., 2019). Consequently, the top 10 routes were designated as the primary paths for analyzing key paths and branching paths. The outcomes are illustrated in Figure 3, which encompasses 28 papers. In this depiction, circles represent nodes, green denotes source nodes, red signifies links, blue indicates sink nodes, and arrows symbolize the flow of information. The nodes are identified by the author's last name and the publication date in English. When multiple authors are involved, only the first letter of their last names is employed, with capitalization. For instance, "SacksEL2004" signifies a publication with three authors, where the first author is Sacks (R), the second author is Eastman (CM), denoted by the initial letter E, and the third author is Lee (G), identified by the initial letter L. Finally, the publication date, 2004, is appended. The trajectory depicted reveals six source nodes at the outset, 22 links in the middle section, and two sink nodes toward the conclusion. The findings of this study can be categorized into four distinct phases, as evident in Figure 3.

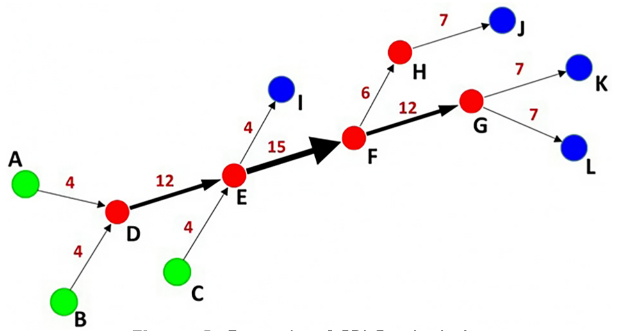

Figure 2. Example of SPLC calculation

BIM standardization

The main path source, which began in 2000, can be divided into three groups, which are discussed below:

1. Parametric Design: Monedero (2000) asserted that non-parametric computer-aided design models pose challenges due to their substantial size and the effort required for content adjustments. The parametric design approach, as suggested by Sacks et al. (2004), is founded on a set of interactive rules and algorithms that govern the principles and relationships of relevant parameters, forming the foundation for architectural design modifications. The evolution of CAD software, according to Sacks et al. (2004), has transitioned from traditional 2D planar drawings to a dynamic 3D visual design environment with simulations. This contemporary CAD system no longer relies solely on geometric lines to represent physical building elements like columns, beams, and walls; it embraces a parametric design concept capable of describing the characteristics of building elements, including dimensions, materials, and colors. Lee et al. (2006) delved into the integration of design and engineering knowledge within BIM system software, emphasizing aspects such as Building Object Behavior (BOB), descriptors, and interpretations. Their focus was on integrating the entire spectrum of building strategy, processes, and technologies to create a digital format that manages diverse building designs and engineering information throughout a building's lifecycle. Jeong et al. (2009) demonstrated that despite advancements in the Industry Foundation Classification (IFC), achieving full interoperability remains a challenge. The imperfect interchange arises from differences in the mapping of internal object structures to IFC objects and attributes. Benchmarking revealed the need for

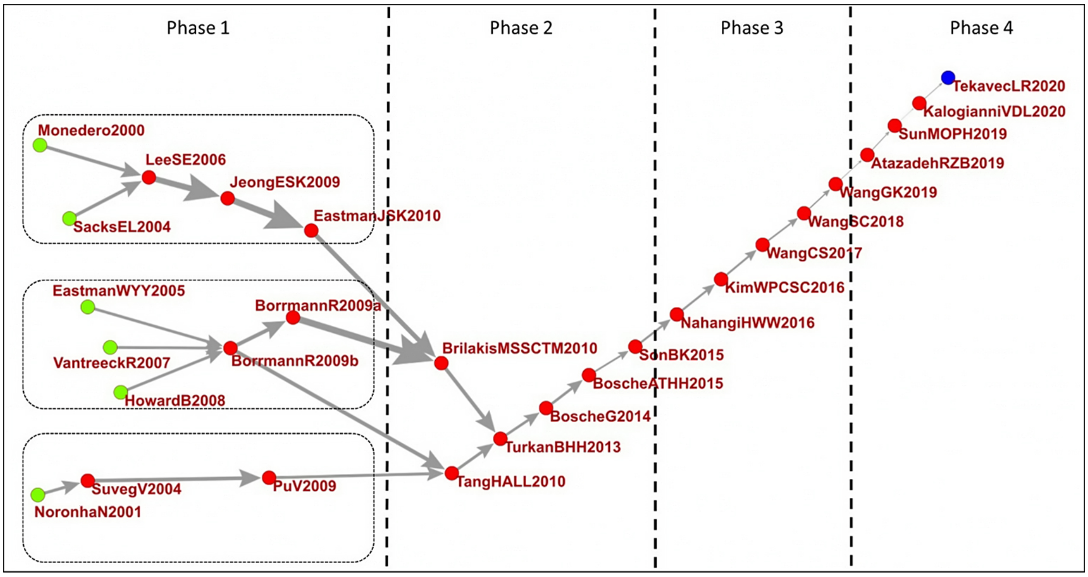

Figure 3. Division of the key-route main path into phases

a mutually agreed-upon standard for modeling and mapping prefabricated building elevations, as well as specifying the required information for each exchange in the workflow. Eastman et al. (2010) viewed the IFC format as a crucial tool for achieving BIM interoperability. However, they noted that IFC did not provide complete interoperability between different BIM software types. Consequently, they outlined specific procedures for the Information Delivery Manual (IDM) to acquire use cases and precise information for exchange purposes.

2. Standards for BIM: Eastman et al. (2005) pointed to the CIMsteel Integration Standard, Version 2 (CIS/2) as an early example of a well-defined product model standard. CIS/2 facilitated the creation of a knowledge base consisting of object models and supported bidirectional information exchange. This standard could accommodate various structural steel lifecycles, encompassing activities from design analysis to detailing, prefabrication, and installation. van Treeck and Rank (2007) initiated the application of 3D building models beyond traditional building design. They identified building diagrams through the pertinent geometry of a given building model, bit-phase geometry, and semantic data. These elements were utilized in constructing an energy model using formulas to simulate building energy consumption. Howard and Björk (2008) delved into the feasibility of BIM, exploring the necessary conditions for its success and the role of Industry Foundation Classes (IFCs) in standardization. They emphasized the importance of making appropriate technologies and standards accessible to companies and advocated for concealing the complexity of IFCs within user-friendly software. Borrmann and Rank (2009a) offered a comprehensive definition of the semantics of orientation models for information modeling within a 3D spatial survey language. They employed point set theory in projection-based orientation models and half-space-based orientation models and introduced the concept of spatial delineation using data structure slot trees. In a related work, Borrmann and Rank (2009b) explored topological operators for information modeling within a 3D spatial query language, utilizing a spatial database for octree-based searching of 3D models.
3. Automatic modeling: Noronha and Nevatia (2001) utilized multiple aerial images to autonomously detect and generate 3D models of linear buildings. Their work highlighted the increasing significance of automatic detection using aerial imagery, foreshadowing its integration with various technological devices and BIM in subsequent years. Suveg and Vosselman (2004) also harnessed aerial imagery as a data source for building reconstruction. Their paper introduced a 3D building reconstruction method that merged aerial image analysis with a comprehensive 2D GIS database and domain knowledge. This combination leveraged the unique strengths of imagery (high resolution, accuracy, and abundant information) and GIS data (comparatively straightforward interpretation) to reconstruct building models. Pu and Vosselman (2009) proposed a technique for automatically reconstructing building façade models based on ground-based laser scanning data. They identified features within a segmented laser point cloud and used these features to create feature polygons and hypothetical components, which were then combined to form polyhedral building models.

BIM for integrated implementation

Brilakis et al. (2010) elaborated on the challenges of modeling completed buildings, noting the time-intensive nature of implementing as-built data modeling. Given the multitude of existing buildings, they proposed a solution involving a combination of technological approaches, such as laser scanning, computer vision, image measurement, machine learning, and parametric object modeling. Their framework presented potential solutions and included preliminary experiments aimed at automating as-built modeling to the greatest extent possible. Tang et al. (2010) demonstrated how these techniques could be employed to automate the BIM creation process. They delineated this process into three fundamental operations: geometric modeling, object identification, and relational modeling of objects. Additionally, they explored potential applications for automated BIM generation, detailed the primary methods employed by these algorithms for representing shape, identification, and relationship knowledge, and outlined approaches for evaluating algorithm performance and monitoring advancements in the field.

Turkan et al. (2013) utilized data from the analysis of reinforced concrete and steel structures to develop an automated four-dimensional model recognition-driven progress tracking system. This system transformed each object into its actual real value, significantly enhancing progress tracking accuracy and providing better support for project-related functions such as cost estimation. Bosché and Guenet (2014) noted that the advancement of terrestrial laser scanning (TLS) and BIM had the potential to enhance surface flatness control efficiency and improve the overall quality of dimensional control operations. Their results illustrated the feasibility of utilizing TLS for standard dimensional control procedures. Bosché et al. (2015) emphasized the growing demand for tools that automate the processing of 3D laser scanning data from completed buildings, particularly for comparing this data with original plans. They monitored the condition of mechanical, electrical, and plumbing (MEP) elements using round sections of pipelines, conduits, and ducts. Their integrated approach, combining "scanning and BIM", allowed for more reliable and automated comparisons between as-built and planned round-section MEP work. This automation facilitated real-time progress tracking, percentage completion calculations, and the generation of accurate as-built BIM models.

Son et al. (2015) highlighted the growing interest among researchers and practitioners in the field of civil engineering regarding the collection and analysis of 3D as-built status data from large-scale civil infrastructure facilities, whether they were in the construction phase, recently commissioned, or already in operation. They emphasized that the utilization of 3D data derived from completed civil infrastructure extended beyond the construction process and had valuable applications in facility management. Specifically, it proved useful for tasks such as process monitoring and automated layout management.

BIM applications for precast technology

Nahangi et al. (2016) integrated principles from 3D imaging and inverse motion analysis to automate and systematically recalibrate the alignment and perpendicularity of pipe assemblies and steel structure installations, ensuring they met the specified standards. Kim et al. (2016) introduced a non-contact dimensional quality assurance method for full-scale precast concrete components by combining laser scanning with BIM. They employed primary component analysis to establish a connection between point cloud data-derived models and the corresponding designed BIM models, enabling precise assessments of critical quality criteria for full-scale precast concrete elements.

Wang et al. (2017) addressed the importance of reinforcement bar positioning in precast reinforced-concrete members for structural performance. They developed an automated technique for determining the positioning of reinforcement bars using color laser scanning data. In the study by Wang et al. (2018), they recognized that actual dimensions of precast elements are often stored manually in paper documents or Microsoft Excel spreadsheets. To alleviate this, they developed an automated approach to dimensioning precast concrete bridge panels and generating a BIM model to accurately store the true dimensions of these panels. Wang et al. (2019) employed 3D laser scanning to capture the precise physical condition of a building and subsequently create a BIM model of the actual structure. This process, referred to as "scan-to-BIM", involved four key steps: (1) identifying the required information, (2) specifying the necessary scan data quality, (3) obtaining the scan data, and (4) executing real-world BIM reconstruction.

BIM applications for land cadaster management

Atazadeh et al. (2019) utilized a physical data set repository and legal knowledge embedded within a BIM-based 3D cadastral model to access pertinent information related to the legal ownership of multi-story buildings. This included queries to distinguish between private and common legal spaces, identify physical elements delineating legal spaces, and locate adjacent legal spaces based on specific building elements. Sun et al. (2019) concluded that it was feasible to integrate cadastral information with BIM/GIS at both conceptual and data levels, resulting in enhanced presentation and visualization of 3D cadastral boundaries.

Kalogianni et al. (2020) highlighted that land management practices worldwide still predominantly relied on 2D-based systems. They emphasized the significance of 3D Land Administration Systems (LAS) within the Spatial Development LifeCycle (SDC), underscoring the potential for greater utilization of BIM/IFC data to integrate various systems into the SDC. Tekavec et al. (2020) presented and discussed a methodology for modeling 3D cadastral datasets. They also validated the importance of modeling datasets in the context of developing efficient processes for managing 3D cadastral data.

The results reveal the presence of two nodes at the end of the path. One signifies the evolution of 3D cadastral data management in conjunction with BIM, while the other denotes the integration of Internet of Things (IoT) with BIM. The former node has gained momentum thanks to advancements in GIS technology tailored for smart city applications. These two distinct dimensions contribute to the establishment of comprehensive solutions for smart cities. The development and convergence of GIS and BIM further enhance operational efficiencies and streamline management processes. As researchers progress towards the latter node, which involves connectivity to IoT along with technologies such as Artificial Intelligence (AI), cloud computing, big data analytics, ontologies, blockchain, Virtual/Augmented Reality (VR/AR), and machine learning (ML), they can offer an expanded array of services to benefit society. These phases encompass stages 5 and potentially even stage 6 of this trajectory.

5. Conclusions

In recent years, the global construction industry has witnessed a remarkable surge in interest and adoption of BIM. This study endeavors to comprehensively analyze the diffusion and progression of knowledge pertaining to BIM in the realm of construction engineering applications, employing a specialized analytical tool known as MPA. By leveraging this methodology, we aim to unveil the intricate patterns and trends that have shaped the trajectory of BIM within the construction industry. The research sample comprises a substantial collection of 3,761 academic papers, all of which are intricately woven around the theme of BIM applications in the construction sector. These papers were meticulously gathered from the esteemed ISI Web of Science database, ensuring a robust and representative dataset that captures the essence of BIM-related research and development within the industry. To embark on this knowledge exploration journey, the study commences with an extensive investigation into the trends in paper publications over the years. This analysis offers invaluable insights into the ebb and flow of scholarly interest and contributions to the field of BIM in construction engineering. By calculating traversal counts along the search path links, the study gains a deeper understanding of the developmental trajectory of BIM in construction engineering. The research originality stems from its trajectory, illuminated by the perspective of MPA, progressing through four discernible stages: (1) BIM Standardization: This initial stage marks the foundational efforts toward establishing standardized practices and principles for BIM implementation within the construction industry. (2) BIM for integrated implementation: in the second stage, we witness the assimilation of BIM into real-world construction projects, where its potential for enhancing project management, design, and execution becomes evident. (3) BIM applications for precast construction: Stage three highlights the specialized role of BIM in precast construction, where its capabilities are harnessed to streamline and optimize processes related to prefabrication. (4) BIM applications for land cadaster management land cadaster management: finally, the fourth stage explores the extension of BIM's utility beyond traditional construction, into the realm of land management, where it plays a pivotal role in facilitating efficient and informed decision-making.

The discoveries and originality not only illuminate the historical backdrop but also provide a framework for comprehending the changing terrain of BIM in the construction sector. As BIM continues to evolve and transform the way we conceive, design, and construct buildings and infrastructure, this study serves as a valuable compass guiding researchers, practitioners, and policymakers in their exploration of this dynamic field. Following MPA, investigating potential correlations between the academic stature of influential authors and their significance on the main path is worthwhile. Future research directions include expanding the number of key-route segments to uncover development trends in various sub-domains. Employing cluster analysis methodologies and tools can help identify node clusters within trajectories, shedding light on key developmental paths in major sub-domains and facilitating the mapping of interactive knowledge diffusion networks. Moreover, applying MPA to other impactful emerging technologies like Industry 4.0, virtual reality, IoT, artificial intelligence, and big data can offer valuable insights for the betterment of humanity.

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Availability of data

All data, models, and code generated or used during the study appear in the submitted article.

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