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EXPLORING BIM TECHNOLOGY DEVELOPMENT USING PATENT CITATION ANALYSIS: USA CASE STUDY

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Abstract. Broadening the perspective on technology and stakeholders within the construction sector, this study aims to uncover the trajectories of BIM's technological progression, alongside the interconnected industries and knowledge networks. Information in Derwent Innovation's patent database originates from the United States Patent Database (USPTO). Initially, 1,062 patents related to BIM were gathered to form a patent citation network. The subsequent stage of expanding patent citations involved accumulating a total of 9,755 patents. The main path is composed of three streams: Stream I is used for the construction and application of 3D models, Stream II is used for the presentation of 3D images, and Stream III is used for the automatic analysis of architectural information. This study also uses edge-betweenness clustering for cluster analysis and conducts a more in-depth main path study of the specific patent clusters on the main path. These findings are: (1) Energy consumption management control, (2) 3D building modeling for design and construction, (3) Asset tracking, monitoring, and security monitoring. The development of BIM should be directed towards the integration and application of transformative information and communication technologies. Integration with innovative technologies such as the Internet of Things, big data, artificial intelligence, and 5G is an important trend.

Keywords: building information modeling, main path analysis, cluster analysis, citation network, patent analysis.

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1. Introduction

Building information modeling (BIM) is an attractive topic to the construction industry worldwide. The emergence of BIM has had a significant impact on construction. However, given the rapid and extensive progress in the development of BIM technology, it is important to understand the trends in technological development and knowledge diffusion. For the development of a technology in a field, patents are often considered to be a useful indicator (Hall et al., 2000; Kim et al., 2008). Patent information allows companies to understand the patent status of competing companies and is also a useful technical document in its right. Patent information can also be investigated prior to the development of technological research. This approach not only avoids wasteful duplication of research, but also helps to identify promising research topics. Patents are therefore an important indicator in the formulation of technological research and development guidelines and of industry analysis. Patents also play an important role in business strategy planning. Therefore, analyzing BIM patents to keep abreast of technological developments and trends in knowledge diffusion in this field is chosen.

Citation network analysis is reliable and effective methods in the field of contextual analysis. It constructs a citation network through the citation relationships between documents in order to find valuable information in them. Here, considering the area of patent analysis as an example, patent citation analysis is often used to estimate the value of a patent. In addition to reflecting the value of individual patents, the citation context can also reflect the knowledge flow of the enterprise or patent subject in terms of knowledge diffusion. Main path analysis (MPA) is frequently used in the analysis of citation networks

(Liu et al., 2019). Hummon and Dereian (1989) proposed MPA as a method for validation of literature in the field of DNA. There are three advantages of using the main path method to analyze citation networks. MPA serves as a tool to unveil a technology's trajectory. Instead of showcasing patent values, this approach delves into technology development paths using patent citations. Firstly, it condenses intricate citation networks into concise representations of nodes and links. Secondly, it highlights primary advancements in science and technology, offering a clear introduction for newcomers to the field. Thirdly, it identifies pivotal nodes in the historical evolution of a specific field (Liu & Lu, 2012). To present a comprehensive overview of BIM technology and expand the perspective on both the technology itself and the stakeholders in the industry, it's imperative to address the following aspects: the key contributors in BIM advancement, the diffusion of technology among them, and the critical technologies being developed in this phase (Hosseini et al., 2018; Khudhair et al., 2021).

The objective of this study is to identify the technology development paths and industry knowledge networks and to provide a comprehensive understanding of the technology development and industry interactions in the BIM field through the application of two different methods, namely main path analysis and cluster analysis. The study commences by conducting an extensive literature review encompassing (1) BIM applications, (2) Applications for citation analysis involving patent citation and main path analysis, and (3) Applications for cluster analysis aimed at probing research gaps. This process aids in pinpointing a particular technology domain, outlining the preliminary patent scope, and subsequently gathering patents relevant to that specific technology area. Other sources of knowledge, such as books, papers, online resources, and product manuals, are not included due to the study scope focusing exclusively on patents.

2. BIM applications

The genesis of BIM traces back to the building description system (BDS) formulated by Charles M. Eastman, a professor in the Department of Building and Information Engineering at the Georgia Institute of Technology in the USA, during 1974–1975 (Eastman, 1975). The BDS, introduced by Eastman, encompasses parametric design principles and facilitates the extraction of profiles, planes, oblique projections, or perspective drawings from a unified database. Alterations made once automatically synchronize all visual representations, ensuring consistency across illustrations. Additionally, it enables the effortless generation and exportation of quantitative analyses, cost estimates, and material quantities (Eastman & Siabiris, 1995). Over time, the BDS has evolved into the building product model (BPM), portraying the seamless transfer of information between contemporary and future design applications in an integrated fashion. The generic building model (GBM) concept emerged to investigate the feasibility of construction and construction management (Eastman, 1999). Building product models (BPMs) are acknowledged for furnishing comprehensive, consolidated information on building elements spanning the entire lifecycle, encompassing conception, design, construction, and demolition. These BPM concepts, technologies, and standards serve as the foundational framework for BIM. The term "BIM" was coined by Jerry Laiserin as a marketing strategy, amalgamating the information technologies offered by Autodesk, Bentley Systems Software, and Graphisoft. BIM denotes a strategy aimed at delivering cutting-edge design software and solutions to the construction industry, encompassing various technologies related to the creation, management, and application of digital 3D building and civil engineering product information models. BIM has undergone significant evolution, demonstrating remarkable scalability from its foundation in 2D (comprising floor plans, elevations, and sections) and 3D models. Its expansion spans higher dimensions by incorporating additional information related to the same model, encompassing 4D (Construction Scheduling, Time), 5D (Cost), 6D (Sustainability), and 7D (Facility Management). Subsequently, advancements led to the emergence of 8D (Health and Safety) (Kamardeen, 2010), 9D (Lean Construction) (Sacks et al., 2010), and 10D (Industrialization) (Babič et al., 2010). These extended applications substantially mitigate information gaps during transfer and significantly diminish the risks and costs associated with project execution.

3. Applications for citation analysis

3.1. Patent citation

Patents serve as crucial markers for corporate R&D and innovation. While an individual patent represents a singular technical document, exploring the connections among a collection of patents unveils diverse information. A primary role of patent literature is to unveil and disclose technology advancements. Technology disclosure enables latecomers to leverage past breakthroughs and innovations, fostering further technological advancement. Frequently, technological developments are described through patent keyword analysis and patent citation analysis. For instance, employing keyword-based patent maps can unveil fresh technological prospects (Lee et al., 2009; Pan et al., 2021; Park et al., 2018, 2020; Son et al., 2012). While these methods often pinpoint pivotal technologies, they barely trace the evolution of technology or unveil the dissemination of knowledge among participants in the field.

Citations serve as references to previously published or unpublished documents, acting as markers of knowledge sources and enabling the tracing of a scientific field's evolution (Garfield et al., 1964). Similar to academic paper citations, a patent citation within a patent document acknowledges prior art by the applicant, inventor, or examiner (Alcácer & Gittelman, 2006). These patent citations form networks of knowledge, utilizing diverse techniques for knowledge network identification (Breschi et al., 2004). They are instrumental in tracking technology trajectories (Bruck et al., 2016; Érdi et al., 2013), uncovering the transfer of knowledge and innovation between countries (Almeida, 1996; Hu & Jaffe, 2003), and identifying the flow of knowledge among patent holders (Jaffe et al., 2000; Sharma et al., 2016).

Within the patent citation network, a patent referred to by others is termed a cited patent, while a patent referencing technology disclosed by others is called a citing patent. A cited patent precedes a citing patent, establishing a directional citation relationship between them. Typically, this relationship flows from the cited patent to the citing patent, demonstrating the transfer of knowledge and the direction of technological progression. The patent citation network primarily comprises nodes and links, with each node representing a patent and the link indicating a cross-citation relationship between patents. A technology development source not referenced by others is termed the source, while a patent devoid of citations is termed a sink, representing the final node in the current technological development. Knowledge dissemination occurs from the source to the convergence node. Therefore, an analysis of patent citation networks aids in comprehending the structure and path of scientific and technological advancements within the field (Cho et al., 2021).

3.2. Main path analysis

Main path analysis, a technique within social network analysis (SNA), was initially introduced by Hummon and Doreian in 1989 to track the primary flow of knowledge within a scientific or technological domain, utilizing citations from academic or proprietary literature (Hummon & Dereian, 1989). SNA itself originated as a foundational method of analysis in the 1930s, pioneered by Jacob Moreno and Helen Jennings. This quantitative research approach utilizes systematic terminology to depict patterns in relationships, employing sociograms and network theory to represent society as a network of diverse relationships.

The subsequent release of Pajek software by Batagelj and Mrvar (1998) allowed for the graphical representation of expansive citation networks, offering clarity regarding citation interconnections and the direction of knowledge dissemination. Master path analysis aims to discern all feasible routes from a source to a sink within a citation network and computes information flow between nodes via algorithms. These algorithms gauge the volume of information transfer (or traversal counts) between two nodes, employing various methods such as SPC (search path count), SPLC (search path link count), SPNP (search path node pair), NPPC (node pair projection count), and others. Additionally, pathways with substantial information traffic can be linked to delineate significant routes and construct master paths through path-tracking methodologies (Verspagen, 2007). Common path-tracking methods encompass local main-path, global main-path, key-route main-path, and global key-route main-path tracing techniques, each offering distinct viewpoints. Different trajectory patterns emerge based on the chosen viewpoint for analysis.

4. Applications for cluster analysis

Clustering involves segregating more homogeneous documents within a citation network (Newman & Girvan, 2004). The underlying concept relies on the idea that if a cluster of patents all reference the same patent and receive citations from an identical number of patents, it implies a likelihood of shared patent knowledge among this group. Consequently, cluster analysis consolidates these closely associated patents into the same grouping. Linkage-based clustering stands as a primary method in citation network analysis. Various clustering techniques exist, including K-means (Shanie et al., 2017), edge-betweenness (Mazlumi & Kermani, 2022), self-organizing map (SOM) (Bamakan et al., 2021), among others. Notably, edge-betweenness clustering, also recognized as the Girvan–Newman algorithm, holds wide application in patent analysis (Newman & Girvan, 2004). The "edge-betweenness" value is perceived as an indicator: a higher value suggests that a particular line segment likely connects two distinct communities. Hence, the algorithm iteratively computes these values for all lines, systematically eliminating those with the highest "edge-betweenness" to dismantle the network gradually. Additionally, seeking potential combinations of subgroups helps ascertain the optimal number of subgroups by assessing the modularity of the grouping coefficient.

The clustering method initially computes the edge-betweenness for all segments within the cited network graph, subsequently eliminating the segment with the highest edge-betweenness value. This process iterates, recalculating edge-betweenness and removing the highest-ranked segment until the network bifurcates into two distinct subnets. With each removal, the edge-betweenness for all network segments is re-evaluated until all segments have been eliminated. This culmination marks the completion of network clustering for this division, which is then computed and documented. Continuing with the recalculation and deletion steps leads to further segmentation, allowing the collation of calculations and records into groups. This process halts once all links within the network are deleted. Subsequently, the clustering pattern exhibiting the highest clustering coefficient is identified as the optimal outcome of the cluster analysis. Following the execution of the edge-betweenness clustering method, a sequence detailing the removed segments is generated, with each stage representing a potential clustering outcome. The ultimate result of this cluster analysis method is determined by selecting the stage showcasing the largest clustering coefficient. This coefficient primarily measures the structural integrity of a network post-clustering. A high clustering coefficient indicates strong inter-node connections within each cluster, with relatively sparse inter-cluster connections. Essentially, a well-clustered network exhibits stronger internal ties within clusters compared to a random network.

5. Proposed methodology

5.1. Data collection

The decision to gather data from the United States Patent Database (USPTO) was based on the substantial quantity and quality of patent applications within this repository. The citations provided by the US patent data are more comprehensive and transparent (Ansell et al., 2018; Cho et al., 2023). For this study, patent and associated citation data were procured through Derwent Innovation, a leading patent database service, in February 2022. Given that the term BIM originated in the 2000s, the data collection's initial year was set to 2000.

Initially, a query string consisting of keywords such as ALL = (building ADJ information ADJ modeling or building ADJ information ADJ model or building ADJ information ADJ modeling or building ADJ description ADJ system or building ADJ product ADJ model) OR TID = (building ADJ information ADJ modeling or building ADJ information ADJ model or building ADJ information ADJ modeling or building ADJ description ADJ system or building ADJ product ADJ model) OR ALL = (BIM and construction) AND AD ≥ (20000101) was constructed. However, it was observed that certain patents related to medical and organic chemical technology were inadvertently included in this collection. To rectify this, the International Patent Classification (IPC) codes A61 (MEDICAL OR VETERINARY SCIENCE; HYGIENE) and C (CHEMISTRY; METALLURGY) were utilized to exclude the relevant patent information that did not align with the scope of this study. Consequently, the final search string was adjusted to ALL = (building ADJ information ADJ modeling or building ADJ information ADJ model or building ADJ information ADJ modeling or building ADJ description ADJ system or building ADJ product ADJ model) OR TID = (building ADJ information ADJ modeling or building ADJ information ADJ model or building ADJ information ADJ modeling or building ADJ description ADJ system or building ADJ product ADJ model) OR ALL = (BIM and construction) AND AD ≥ (20000101) NOT IC = (A61 or C).

A corpus of 2,434 licensed US patents served as the foundation for our analysis. Subsequently, the patent citation network was refined by excluding less relevant and non-citing patents, resulting in a subset of 1,062 patents. Expanding the patent system through level 1 citation increased the scope to 3,960 patents. Further extension to level 2 citation involved the removal of less relevant, non-citing, and duplicate patents (some existing in both public and publication numbers within the database). As a result, a final dataset comprising 9,755 patents was obtained for this study. In this research, SPLC is utilized to calculate information traffic (weight), coupled with the application of the global key-route main-path tracking method. The concept of the "global key-route main path" revolves around identifying segments within the citation network bearing substantial information traffic. These key-route segments extend both forward and backward from their head and tail points, revealing the primary path and providing a holistic perspective on technology development's broader context (Liu & Lu, 2012).

Utilizing the EF line in Figure 1 as an example for SPLC computation involves tracing nodes A, B, C, D, and E (including E itself) culminating at node E's endpoint. This arrangement permits five potential paths within this segment: A-D-E-F, B-D-E-F, C-E-F, D-E-F, and E-F. Progressing from the head end (node F) towards each convergence node (blue nodes, encompassing J, K, and L) unveils three viable paths for each: F-H-J, F-G-K, and F-G-L. Consequently, the SPLC value for the E-F segment reaches 15 (5 × 3 = 15). By employing this methodology, SPLC values for all interconnected lines can be determined.

As depicted in Figure 1, the line segment's thickness correlates with its SPLC value. Within this network example, the E-F segment boasts the highest SPLC value, indicating its prominence as the most pivotal pathway for knowledge dissemination. Consequently, the pursuit of the main path initiates from this segment. Setting the number of key-routes for the overall key-extension master path to 2 (Key-Route 2), the top two SPLC values (E-F and F-G) are designated as key-routes. Extending these line segments outward establishes the total key extensions of the main path within the cited network, with the core segments (E-F and F-G) forming the foundation, as illustrated in Figure 2.

As outlined in the preceding section, main path analysis facilitates the identification of the largest clusters within citation networks. The literature contained within these citation network clusters exhibits significant correlation.

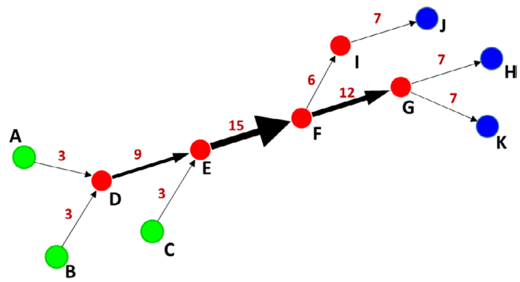

Figure 1. Example of main paths for SPLC calculation

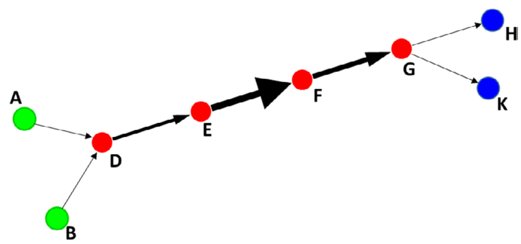

Figure 2. Example of main paths for searching the global key-route main path

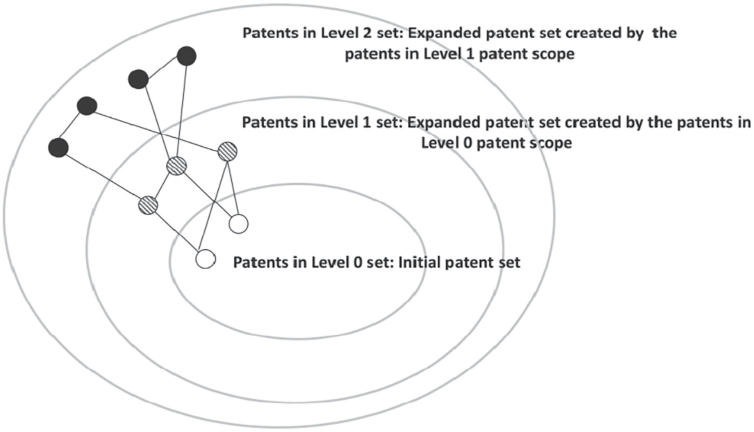

Figure 3. Expanded patent sets

However, to ensure the data integrity of the citation network for subsequent analysis, this study introduces a citation network extension method (Abood & Feltenberger, 2018; Cho et al., 2023). This method involves utilizing citations cited by the examiners of each patent application to extend the patent citation network. Examiner-cited literature is typically more pertinent to the invention of the patent application, thereby reducing potential noise introduced during the citation path extension. Additionally, this method can transition from an initial patent set (level 0 patent set) to a Level 1 patent set, transforming a first-order bootstrap network into a second-order bootstrap network. For a more comprehensive clustering of the bootstrap network, an extension to a level 2 patent set is feasible, as depicted in Figure 3. Figure 4 illustrates the process followed in this study. The initial step involves pinpointing a particular technology domain, delineating the initial scope of patents, and subsequently gathering patents associated with this technology. Once the initial patent set is secured, extensions to the literature are made through a network of citations. Employing main path analysis and cluster analysis on this extended patent set enables secondary main path analysis within each cluster. This secondary analysis helps identify technology clusters, significant paths containing key patents, and facilitates the examination of technology trends and profiles. Main path analysis determined the selection of twenty key-routes, indicating the inclusion of the twenty most crucial links within the evidence network. For the study, a key-route number of 5 was chosen as the foundation, considering the relatively limited data available for each technology group.

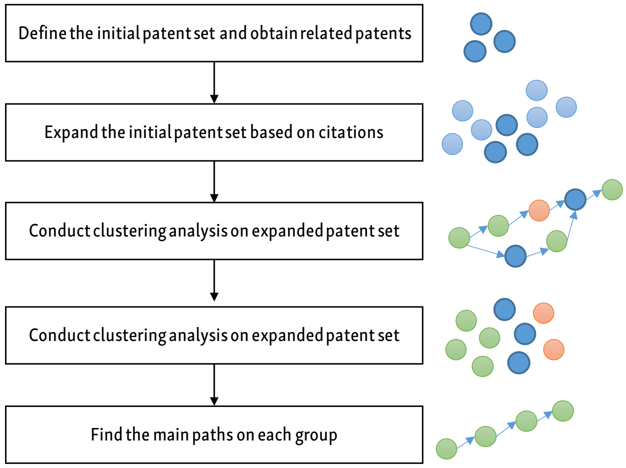

Figure 4. Procedures of the research method

5.2. Main paths of the Level 2 Expanded Patent Set

This section reveals the outcomes derived from the main-path analysis conducted on the Level 2 Expanded Patent Set. The graph's grey link thickness corresponds to the link's significance, represented by its SPLC value. Each node is labeled with its patent number, filing year, and publication year, denoted by underlining the patent (e.g., US6272447B1_1999_2001, where US6272447B1 signifies the primary patent number applied for in 1999 and published in 2001). Nodes labeled with FM denote a patent family, with the subsequent patent number indicating the family's parent patent number. The green node signifies the source, while the blue node represents the sink. Diverging paths often indicate the branching of a technology into different concepts, solutions, or implementations. Conversely, convergence signifies the potential merging of various ideas, solutions, or implementations for the next generation of technology.

In the Level 2 Expanded Patent Set, Figure 5 illustrates the outcomes of the key-route 20 main-path analysis focused on patents filed after 2000. The main paths encompass 32 nodes, with thirty representing individual patents and two representing a patent family. These main paths are delineated into three distinct streams, each depicting the evolution of technology. Each stream's depiction entails Technology Themes, Key Players, and Representative Technologies.

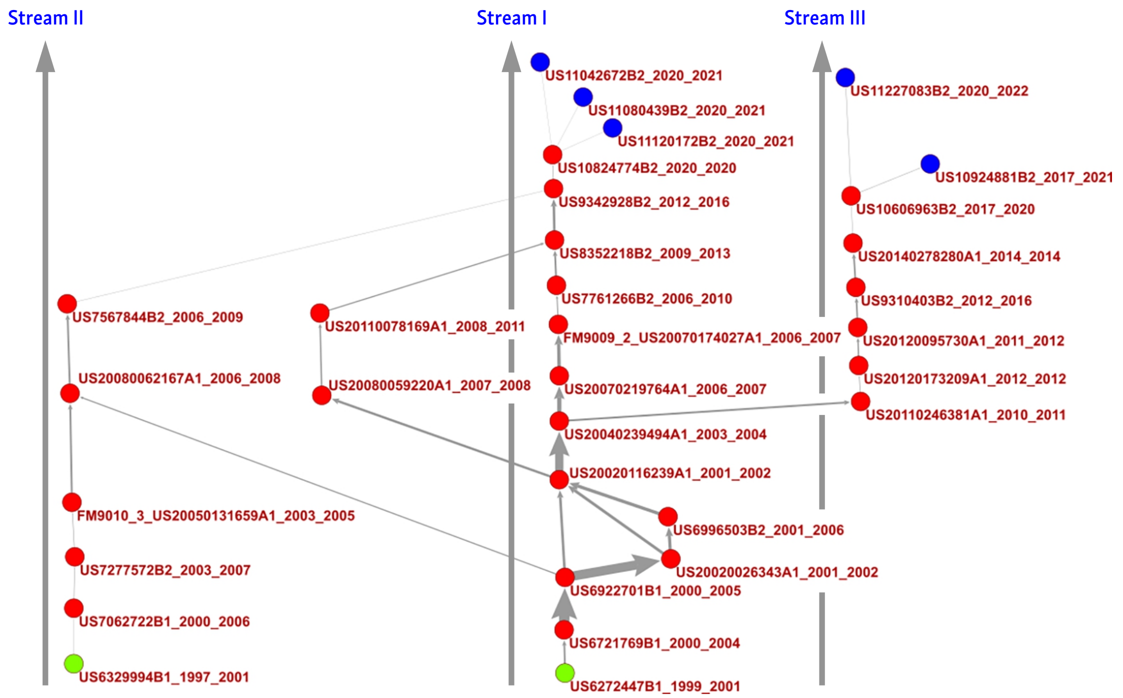

Figure 5. Key-route main-path analysis on the Level 2 Expanded Patent Set at Key-Route 20

Stream I: 3D Model Building and Applications

Stream I primarily revolves around the creation and utilization of 3D models, aligning closely with the conventional comprehension of BIM. This stream encompasses a higher count of patents with substantial information flow (SPLC) and serves as one of the origins of the main path. Originating from Scottsdale Building Systems Limited in New Zealand, the filing of US6272447B1 (current assignee: NUCONSTEEL Corp., USA) in 1999 marks its source. The patent involves modeling each structural element of a plan as a fundamental component using a computer, converting these components into three dimensions based on specified positions and orientations in the plan. Spatial analysis allows for length specifications and connection details of structural elements. Furthermore, the patent details the formation of structural elements on a forming machine per output specifications and connection features, enabling their assembly into a building frame. Additionally, components are prefabricated on a portable roll-forming machine according to a pre-determined design plan.

US6721769B1 (current assignee: Extreme Networks Inc., USA), filed by Wireless Valley Communications Inc. in 2000, and US6922701B1 (current assignee: Havenomics LLC., USA), filed by Newerhome Technologies Inc. (current assignee: Havenomics LLC., U.S.A.), boast the highest SPLC values in this stream, signifying a substantial impact on the overarching technology development within this path. The primary description of US6721769B1 focuses on inputting 2-D images (like grating scans or design drawings) of the physical environment and systematically converting them into a 3-D environment database, facilitating design, prediction, measurement, and optimization of wireless communication systems. On the other hand, the main description of US6922701B1 involves a CAD format, commonly employed in general plan sets, encompassing a fundamental physical description of the building.

Within this stream, three patents – US11042672B2, US11120172B2, and US11080439B2 – were collectively filed in 2020 by Middle Chart LLC. These patents center on leveraging wireless communication among intelligent sensing devices to ascertain location within a specified area. US11042672B2 introduces a method and device tailored for tracking medical procedures. Meanwhile, US11120172B2 offers a method and apparatus for determining location and direction of interest based on multiple wireless communications. Lastly, US11080439B2 serves to automate environmental conditions within a cold storage facility, ensuring precise, consistent, and efficient control while enabling easy tracking of people or objects within the facility.

Stream II: 3D Image Presentation

Stream II predominantly focuses on the presentation of 3D images and stands as one of the origins of the main path. Stemming from Zapa Digital Arts Ltd. in Israel, the source patent is US6329994B1 (current assignee: Dg Holdings Inc and Daz Productions Inc., USA), filed in 1997. This patent involves generating an animated sequence on a computer-driven graphic display to define a three-dimensional geometric representation of an animated scene.

US7567844B2 (current assignee: Innovation Asset Collective, Canada), applied for by Honeywell International Inc. in 2006, and US International Design and Construction Online Inc. (current assignee: Eris Technology LLC, Canada), filed in 2006 by Honeywell International Inc., along with US20080062167A1 (current assignee: Eris Technology LLC, Canada), are pivotal in this mainstream, signifying a convergence of two conceptual streams. US7567844B2 revolves around a building management system (BMS) capable of presenting a 3D or 3D-rendered 2D model in various formats (color, grayscale, or black and white). It facilitates the projection of information regarding the location and status of sensors, control devices, etc., within the building onto this model. Meanwhile, US20080062167A1 introduces a system for providing real-time or near-real-time awareness of a structure's status. It involves rendering a 3-D virtual model of the structure utilizing structure-related information, integrating situational awareness information into the 3-D virtual model for user display.

Stream III: Automatic Analysis of Building Information

Stream III revolves around the automated analysis of building information and is connected through the mainstream branch to Abv Holdings LLC's 2010 application US20110246381A1. This patent proposes a methodology for modeling the energy consumption of proposed buildings, aiding investors and building professionals in predicting energy use, sustainability, and cost based on limited building information (such as building type, location, and size) before commencing a building project. This stream concludes with two patents as its sink. First, US10924881B2, filed in 2017 by Husqvarna Ab of Sweden, presents a device designed to detect the location of construction equipment and workers, focusing on analyzing and determining their safety status. Additionally, there's the US11227083B2, submitted in 2020 by Beamup Ltd of Israel, introducing a semantic enrichment structural design system for building floor plans. This patent involves performing semantic richness analysis across multiple spaces using machine learning techniques. It enables the determination of semantic designations for associated spaces by automatically analyzing and editing floor plans according to space-specific functional requirements, thereby adding or replacing new or existing semantic designations.

5.3. Clustering the expanded patent set

The outcomes of the edge-betweenness clustering analysis reveal the division of the Level 2 Expanded Patent Set into twenty distinct technology clusters, as outlined in Table 1. The largest cluster (Cluster 1) encompasses 1,032 patents, while the smallest (Cluster 20) includes 80 patents. A portion of patents from the Level 2 Expanded Patent Set remains unassociated with these technology clusters, mainly constituting isolated nodes within the citation network. Notably, the edge-betweenness clustering approach excels in avoiding the imposition of connections between entities and seemingly unrelated clusters. To gain a comprehensive understanding of the technologies within each group and to delineate significant trends, conducting an individual main-path analysis using key-routes for each technology cluster is imperative. This in-depth examination involves a meticulous study of the technology groups containing patents on the Level 2 Expanded Patent Set's main path. By leveraging the insights from this analysis, we can unravel the pivotal trends and developmental outlines spanning the past two decades. Table 1 encapsulates the technical themes, major contributors, and main-path outcomes for each technology cluster.

5.4. Main paths of technology groups

This section outlines the outcomes derived from both cluster analysis and main-path analysis. Following the cluster analysis, it identified twenty distinct technology groups. From the Level 2 Expanded Patent Set, particular emphasis was given to delving into the Technology Group for a detailed exploration and depiction of patented technology groups via the main path. The selected technology groups containing patents are Technology Group 1, Technology Group 2, Technology Group 6, and Technology Group 11, each detailed below.

Group 1: Energy Consumption Management Control

Group 1, centering on Energy Consumption Management Control, encompasses 1,032 articles. Within this technology group, there have been thirteen Key-Route 5 main-path patents recorded post-2000, featuring two source nodes and one sink node displayed in Figure 6. Among these patents along the path, there are twelve attributed to US companies, as detailed in Table 2. Notably, US6216956B1's ownership has been transferred to the UK-based company Invensys PLC. Notably, the patents within this technology group's overarching key extension main path predominantly originate from the United States. Key players like Honeywell International Inc., specializing in environmental automation controls, and Lennox International Inc., a provider of climate control products, significantly contribute to the development and application of intelligent building technology.

Group 1 primarily focuses on Energy Management Control, aligning with the current drive towards environmentally sustainable development and falling under the purview of 6D BIM. The overarching key extension involves two branches stemming from the main path's proprietary source nodes. The first branch concentrates on technologies geared towards environmental control and energy management within building spaces. It initiates with systems optimizing comfort and curbing energy consumption and costs through predefined user parameters. This branch integrates sensors, meters, and other equipment to autonomously analyze energy usage, facilitating resource management. The second branch centers on networked monitoring methodologies and systems for the built environment (e.g., HVAC, lighting, access control, and security). These systems, operable, integrated, and automated via the Internet, display through a graphical user interface (GUI). Converging at US8527096B2, these two source node branches oversee HVAC system control via a programmable controller. The user interface enables an intuitive switch between room condition displays and thermostat settings, encompassing technology for energy consumption and environmental monitoring. Lastly, US10067516B2 depicts the sink point, determining occupants' activity statuses and setting temperature values based on biofeedback data.

Table 1. Results of key-route main-path analysis for each technology group

Technology Group	Total patents	Patent number of KR5 MPA for each group	Technology theme	Main Assignee (the most owned patents in group)	Patent on overall KR20 MPA
Group 1	1,032	13	Energy Consumption Management Control	Johnson Controls Inc.	Y
Group 2	968	15	3D Building Modeling for Design and Construction	Autodesk Inc.	Y
Group 3	774	24	Computer-Based System to Support Process Operation	International Business Machines Corp.	
Group 4	751	7	Augmented Reality & Virtual Reality Displays	Microsoft Technology Licensing LLC	
Group 5	269	13	Computer-Implemented Method for Generating Three-Dimensional Model	Google Inc.	
Group 6	255	8	Asset Tracking and Monitoring	Honeywell International Inc.	Y
Group 7	199	14	Computing Environment Management	International Business Machines Corp.	
Group 8	177	21	Video Surveillance	Johnson Controls Inc.	
Group 9	173	7	Communication Network for a Computer Learning System	Microsoft Technology Licensing LLC.	
Group 10	167	13	Secure Financial Transaction	Visa Inc.	
Group 11	167	13	Security Monitoring	Honeywell International Inc.	Y
Group 12	146	15	Gaming System	International Game Technology PLC (IGT)	
Group 13	145	8	Processing Data Stream	Oracle Corporation	
Group 14	133	10	Collaborative Document Annotation	International Business Machines Corp.	
Group 15	128	12	Monitoring and Tracking Position of Subject	United Parcel Service of America Inc.	
Group 16	116	8	Controlling Information of Construction Equipment	Caterpillar Inc.	
Group 17	104	6	Point Cloud	Leica Geosystems Holding Ag.	
Group 18	101	12	Radio Frequency Identification (RFID)	Handheld Products Inc.	
Group 19	83	9	Managing Information for Aiding On-Site Building Construction	Trimble Inc.	
Group 20	80	11	Modular Building Structure	Power Solutions International Inc.	

Table 2. Group 1 patent owners and country in the Global key-route main path

Country	Assignee	Publication Number
USA	Automated Energy Inc.	US20030055677A1
	Energyhub Inc.	US20110061014A1
	Honeywell International Inc.	US7702421B2
		US7963454B2
	Lennox International Inc.	US8527096B2
	MCEnergy Inc.	US7818270B2
	Nest Lsbs Inc. | Google Inc.	US9459018B2
	Netbotz Inc.	US6714977B1
	Novar Marketing Inc.	US20020152298A1
	Opower Inc.	US10067516B2
	Siemens Aktiengesellschaft	US20060058923A1
	Tocom Inc.	US6216956B1 (current assignee: United Kingdom, Invensys PLC.)
	Vigilos Inc.	US7016813B2

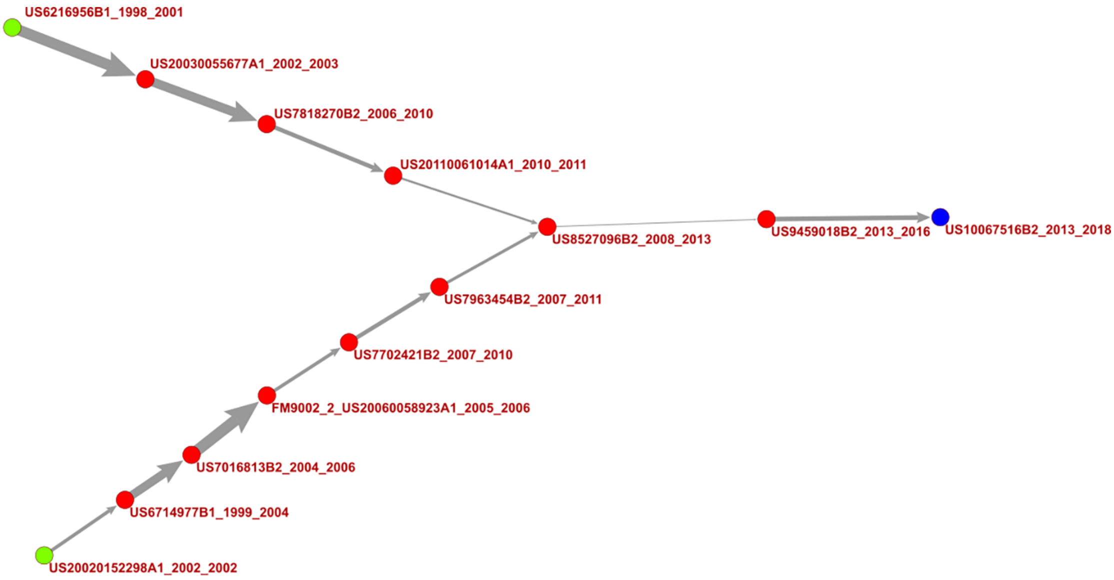

Figure 6. Key-route main-path analysis of Group 1 at Key-Route 5

Group 2: 3D Building Modeling for Design and Construction

Group 2 revolves around 3D Building Modeling for Design and Construction and encompasses 968 entries. This cluster has seen fifteen Key-Route 5 main-path patents since 2000, with one source and one sink node, illustrated in Figure 7. Along this trajectory, ten patents from four countries feature, with seven companies from the USA and one each from Canada, New Zealand, and South Korea contributing to this pathway (refer to Table 3). Notably, Autodesk Inc. holds four patents within this trajectory, being an internationally recognized leader in BIM. It's renowned for coining the term "BIM" and owning the acclaimed Autodesk Revit, a pivotal platform in the BIM landscape. Anguleris Technologies LLC, the second most prolific company within this trajectory, specializes in intelligent BIM content development and offers architectural virtual product installations. Patents from these entities have emerged as key patents within this technology cluster, establishing its significance in shaping the foundation of BIM. The main path within this technology cluster indicates a crucial trend in BIM's development.

Group 2 primarily concentrates on the generation and utilization of 3D building models, aligning with BIM's 2D and 3D scope, marking a crucial cluster in fortifying the fundamentals of BIM. The patent content found in the Global Key-Route Main Path within this technology group warrants individual study and analysis. It can be categorized into four developmental stages, segmented based on the type of technology and its specific application.

Phase 1: Building 3D Information Applications for Spatial Analysis

Key patents within this domain encompass US6272447B1, employing plan-to-3D conversion for prefabrication of structural elements; US6721769B1, utilizing lenticular scanning to translate physical environment data into 3D for wireless communication system analysis; and US6922701B1, integrating CAD format data from floor plans into an interactive profile system, facilitating user interaction via an Internet browser.

Phase 2: Quantitative Analysis of Building Information

The exemplar patent, US20020026343A1, employs a construction material database, graphical item representations, and data input to automate cost estimation across mechanical contracting, electrical contracting, fire protection, and other processes for construction projects. Meanwhile, US6996503B2 utilizes a 2D CAD interface to estimate a bill of materials and generate a material pick list, detailing material specifications, shape, location, and unit costs within a 2D or 3D design drawing. In terms of energy code compliance, US20020116239A1 identifies the most cost-effective building materials or systems to meet energy code criteria while constructing a structure. Lastly, US20040239494A1 leverages a 3D computer-aided design tool or BIM application to produce precise building geometry drawings and automate energy requirement analyses for hospitals.

Phase 3: Automatically Creating Physical Computer-Aided Design Model

The highlighted patent, US20070219764A1, employs a physical computer-aided design (CAD) model to generate flow system pipeline schematics. It facilitates automatic updates to the analysis model and interlinks various physical objects in the model, ensuring adjustments to one part are reflected in other models. On the other hand, US20070174027A1 utilizes an architectural CAD model to autonomously generate a structural CAD model based on user preferences, establishing concurrent relationships between architectural and structural elements. Additionally, US20090273598A1 automatically translates attributes and positional data from beam and column designs in a 2D drawing into a corresponding 3D representation.

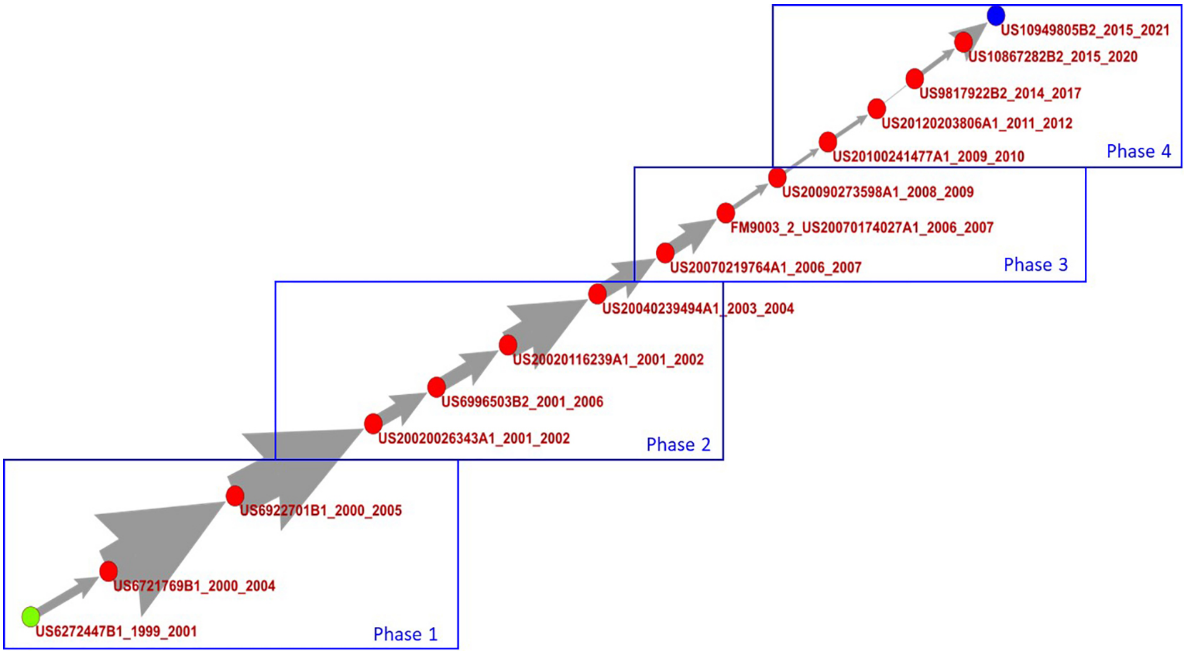

Figure 7. Key-Route main-path analysis of Group 2 at Key-Route 5

Table 3. Group 2 patents and countries in the Global key-route main path

Country	Assignee	Publication Number
Canada	Newerhome Technologies Inc.	US6922701B1 (current assignee: USA, Havenomics LLC)
Korea	El Con System Co. Ltd.	US6996503B2
New Zealand	Scottsdale Building Systems Ltd.	US6272447B1 (current assignee: USA, NuconSteel Corp.)
USA	Wireless Valley Communications Inc.	US6721769B1 (current assignee: USA, Extreme Networks Inc.)
	Johns Manville International Inc.	US20020116239A1
	Murphy Ind Inc.	US20020026343A1
	Autodesk Inc.	US20040239494A1
		US20070174027A1
		US20070219764A1
		US20120203806A1
	Auto Prep LLC.	US20090273598A1
	Scenario Design LLC	US20100241477A1
	Anguleris Technologies LLC	US9817922B2
		US10867282B2
		US10949805B2

Phase 4: Building Information Modeling for Management and Collaboration

The highlighted patent, US20100241477A1, pertains to a construction project management system, particularly for high-rise building construction. This system integrates a broad spectrum of data into a workflow that combines management modeling information and engineering details when inputted. Meanwhile, US20120203806A1 introduces a building information management system that consolidates information from multiple sources – such as project management, facilities management, and building design – into a three-dimensional model, enabling detailed component examination. US9817922B2 can generate new models of various dimensions, including 2D, 3D, and beyond, using existing 3D modeling software like Autodesk Revit, AutoCAD, Vectorworks, Micro Station, ArchiCAD, among others. These newly created models can directly produce physical objects such as windows and doors using robots, 3D printers, and manufacturing machinery. Moreover, US10867282B2 facilitates collaborative automated modeling processes and integrates GPS into BIM and other design platforms, aligning the model with the actual site location. Lastly, US10949805B2 offers a method for collaborative interaction with X-dimensional object models, allowing real-time collaboration between native and newly composed 3D models within popular 3D modeling BIM programs like Autodesk Revit, AutoCAD, Vectorworks, and more.

Group 6: Asset Tracking and Monitoring

Group 6 pertains to Asset Tracking and Monitoring, encompassing 255 articles. This technology cluster has generated eight Key-Route 5 main-path patents since 2000. It involves one source and three convergence nodes, as depicted in Figure 8.

In this stream, patents are owned by five entities across two countries, with four entities from the US and one from China, as indicated in Table 4. The primary patents in this technology cluster's global key-route main path are predominantly from the US. Middle Chart LLC, a US-based intelligent building and automation company, holds up to four of these patents. Honeywell International Inc. also plays a significant role in Asset Tracking and Monitoring. Group 6 primarily centers on applying Asset Tracking and Monitoring technology. The originating patent for this technology cluster on the global key-route main path is US6231188B1, responsible for acquiring facial digital images and pairing them with an eyewear database to create an interactive eyewear selection system. The subsequent patent, US7062722B1, enables visual selection, customization, and evaluation of products (like furniture or eyewear) in a virtual reality setting. This perspective encompasses a 3D model of an actual space and an object within that space. Among the most significant weighted paths are US9342928B2 and US10824774B2. US9342928B2 offers BIM and BMS data (comprising building schematic 3D models and building component operation details) on portable devices. This facilitates technicians in locating specific equipment and conducting inspections or maintenance using portable tools. US10824774B2 enhances healthcare by automatically determining the positions of individuals and equipment while quantifying conditions via automatic sensors. The optimization system can deploy healthcare providers strategically – for instance, organizing equipment and resources according to the needs of a patient undergoing surgery. The ultimate sink nodes are US11042672B2, US11120172B2, and US11080439B2. These patents primarily revolve around the utilization of wirelessly communicating sensors to track object positions and methods for automated monitoring of relative positions, particularly applicable in healthcare, freezer item storage, and similar contexts.

Table 4. Group 6 patents and countries in the Global key-route main path

Country	Assignee	Publication Number
China	Boe Technology Group Ltd	US6231188B1
USA	Honeywell International Inc.	US9342928B2
	Middle Chart LLC	US10824774B2
		US11042672B2
		US11080439B2
		US11120172B2
	Bruce Carlin, Satoshi Asami, Arthur Porras, Sandra Porras	US7062722B1
	University of Southern California	US7583275B2

Group 11: Security Monitoring

Group 11 centers on Security Monitoring and encompasses 167 articles. This technology group boasts a total of thirteen Key-Route 5 main-path patents since 2000, involving five source nodes and three sinks, illustrated in Figure 9. Within this pathway, seven patent holders span four countries. The majority are US-based companies (totaling four), two hail from Canada, while Sweden and the Netherlands each contribute one. Table 5 outlines the patents applied for in this context. Predominantly, the patent holders in this technology group, featured on the Global key-route main path, are telecommunications equipment providers such as Blackberry Ltd. Additionally, another cluster of companies plays a vital role in advancing smart home-security systems, including Honeywell International Inc. and Icontrol Networks Inc.

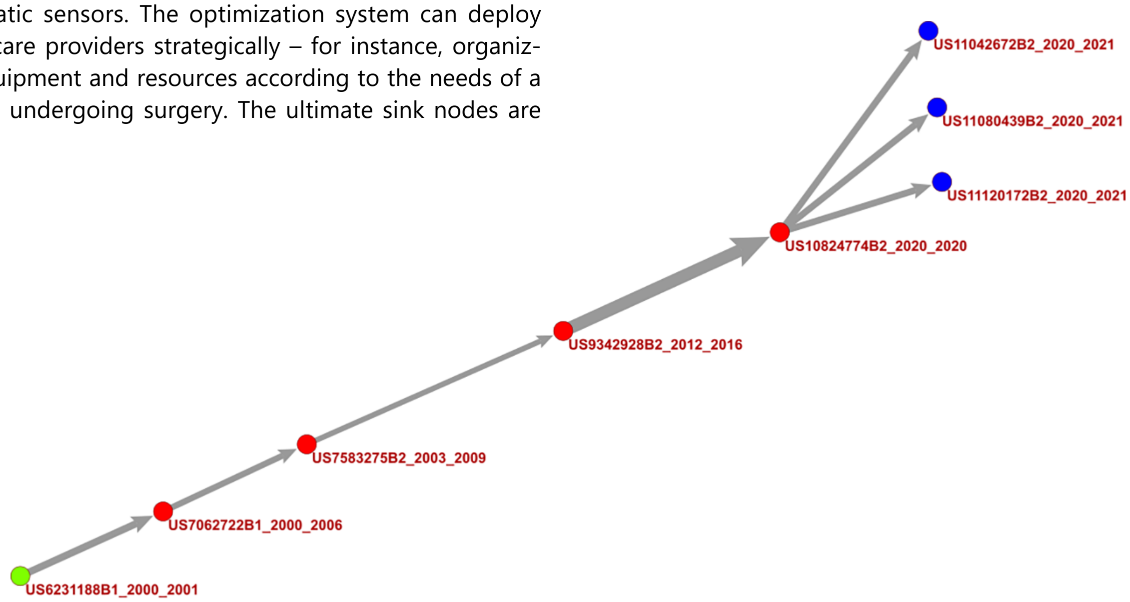

Figure 8. Key-Route main-path analysis of Group 6 at Key-Route 5

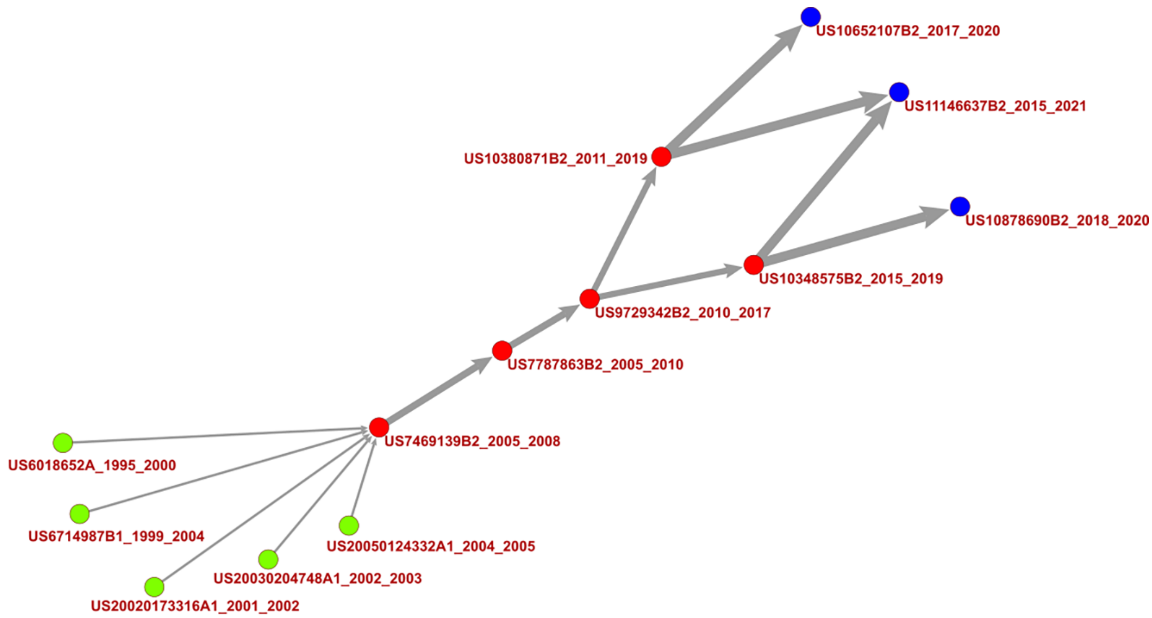

Figure 9. Key-Route main-path analysis of Group 11 at Key-Route 5

Table 5. Group 11 patents and countries in the Global key-route main path

Country	Assignee	Publication Number
Canada	Blackberry Ltd.	US20050124332A1
	Nortel Networks Ltd.	US20020173316A1 (Current Assignee: USA, Rockstar Bidco LP)
		US6714987B1 (Current Assignee: USA, Apple Inc.)
Netherlands	Koninklijke Philips N.V.	US20030204748A1
Sweden	Ericsson	US6018652A
USA	Computer Associates Think Inc.	US7469139B2 (Current Assignee: USA, Google Inc.)
		US7787863B2 (current assignee: USA, Google Inc.)
	Honeywell International Inc.	US10878690B2
	Icontrol Networks Inc.	US10348575B2
		US10380871B2
		US11146637B2
		US9729342B2
	International Business Machines Corp.	US10652107B2

The patents within the Global key-route main path exhibit a more dispersed pattern within this technology group. Nonetheless, these patents predominantly concern the architecture of communication networks associated with mobile communication systems and area locations, eventually converging in US7469139B2. This patent introduces a wireless manager that gathers location information from a mobile device and automatically cross-references this data with the associated access area. If the location data confirms the mobile device remains within the access area, it is authorized for wireless communication with the corporate network. The path culminating in the final sink possesses the highest weight, indicating the pivotal role of the sink node in this technology group. US11146637B2, US10878690B2, and US10652107B2 characterize the final sink, focusing on data transmission from sensors and/or network devices, integrating them into gateways and remote servers, thus enabling users to access an integrated security system. Additionally, a significant forthcoming trend involves the fusion of smart home security systems with IoT applications.

6. Discussion

In general, the final sink of the main path can be split into two segments. The initial part pertains to Stream I's focus on pinpointing locations within a specific area via wireless communication among intelligent sensing devices. The latter involves the utilization of machine learning techniques for automatic analysis and editing of floor plans. These observations imply a necessity for digital transformation within the industrial construction sector. It necessitates a blend of static BIM information with multifaceted functionalities such as "sensory connectivity", "data fusion", and "deep learning". This stands as a pivotal research area in the context of the Internet of Things, big data, artificial intelligence, and 5G technologies.

The cluster analysis outcomes reveal an intriguing expansion from the initial dataset, uncovering numerous BIM technologies beyond conventional recognition. For instance, the main-path analysis outcomes of Technology Group 11 predominantly pertain to communication transmission technology. Nonetheless, the future trajectory of BIM remains intimately intertwined with communication technologies. Especially in BIM data transfer, there's a demand for swift, high-capacity, ultra-reliable, low-latency communication across multiple concurrent connections within the same network infrastructure. This also involves the utilization of associated tools like drones, robots, etc. Essentially, achieving real-time capabilities in BIM necessitates robust communication technologies.

The United States stands out as the primary contributor to BIM-related patents, accounting for over half the patents and patent holders across various technology groups. Notably, key patent holders within the main-path-related clusters predominantly include U.S.-based companies like Autodesk Inc., Johnson Controls Inc., and Honeywell International Inc. These entities uphold significant leadership roles within their respective technology domains. Autodesk Inc. remains a stalwart advocate for BIM technology, consistently innovating and introducing new BIM software. Johnson Controls Inc. capitalizes on its BIM expertise to craft energy analysis models and expedite high-performance building designs. Meanwhile, Honeywell International Inc.'s recent patent, US20220301270A1, illustrates its ongoing integration of immersive, collaborative video surveillance with BIM technology.

7. Conclusions

Main-path analysis offers an expansive perspective on the evolution of BIM-related technologies, revealing crucial trends and focal points within the innovative technology cluster. This analytical method simplifies the intricate web of citation relationships, spotlighting pivotal nodes and connections that form the core context. Throughout its inception, main-path analysis has undergone progressive stages, integrating, expanding, and branching to its current state in knowledge transmission. The key contributions encompass:

1. In this investigation, the Key-Route 20 main path was chosen for the main-path analysis method, spotlighting 32 pivotal patents among the 9,755 BIM patents. The main path branches into three primary streams. Stream I centers on 3D model creation and application. Stream II focuses on the display of 3D images. Stream III primarily delves into the automated analysis of building information.
2. Based on the technology group classification of the patents within the Global key-route main path, Group 1 concentrates on Energy Management Control, aligning with the contemporary drive for environmentally sustainable practices and fitting within the domain of 6D BIM. Group 2 centers on the generation and use of 3D building models, contributing significantly to the framework of 2D and 3D BIM applications, pivotal in BIM's foundational development. Group 6 emphasizes Asset Tracking and Monitoring applications, while Group 11 specializes in Security Monitoring.
3. The progression of BIM needs to merge with the evolution of information and communication technology. The convergence of cutting-edge innovations like the Internet of Things, big data, artificial intelligence, and 5G marks a crucial trajectory for advancement.

There are three primary constraints inherent in this study. Firstly, the analysis focuses solely on patents published after 2000 since the term "BIM" emerged around that time. Secondly, the study predominantly includes US patents, potentially excluding patents filed outside the US. Thirdly, the dataset comprises published US patents, which may lag in reflecting the most current technology developments, given the approximate three-year delay between patent application and granting. Consequently, the study might not fully portray the current technology landscape.

Future research could consider expanding the analysis to encompass patents from diverse regions such as Japan, South Korea, China, and across Europe. These regions have become fertile ground for BIM technology development, with various stakeholders seeking patent protection and market control. A more comprehensive perspective could be gained by examining patents filed in these areas. Moreover, improving patent citation analysis could include incorporating patents from various jurisdictions, such as those with new or existing technology referenced by examiners, to achieve a more comprehensive understanding. For example, integrating digital twins with BIM applications to cover lifecycle and real-time data is a suggested direction for future studies related to clusters, groups, and other methods of analysis.

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Data availability statement

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

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