A bibliometric review of visual computing in the construction industry

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Abstract

In the construction are, visuals such as drawings, photos, videos, and 3D models, play a significant role in the design, build and maintenance of a facility, bringing efficiency to generate, transfer, and store information. Advanced visual computing techniques facilitate the understanding of design contents, work plans, and other types of information shared in the construction industry. Automatic visual data collection and analysis provide many possibilities to the construction industry and a large number of works have investigated how visual computing can improve construction management processes and other problems in the construction area. However, a comprehensive literature review is needed. This study uses bibliometric approaches to review the works published to date, and analyses the development of knowledge, significant research results, and trends. The purpose of this study is to help newcomers to this research field understand knowledge structure and formulate research directions, thereby enhancing knowledge development. From this study, it can be concluded that computer vision is a key axis of improvement. Moreover, building information modeling (BIM), laser scanning, and other visualization-related techniques are also important in advancing the construction area.

Keywords: visual computing; bibliometric analysis; construction application; building information modeling; laser scanning; augmented reality; construction management.

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1. Introduction

Visual computing is a general term that covers the research area for collecting and processing images, videos, 3D models, and other types of visual data[1]. It is significant to store, transfer, present, generate, and analyze visual information because people rely most on visual information to understand the outside world. Visual computing provides many possibilities for improving industries, such as the construction industry[2]. In the construction industry, engineers traditionally use drawings and documents to represent design information and use photos or texts to record on-site information. Nowadays, building information modeling (BIM) makes it possible to build an integrated database during the life cycle of construction projects[3]. In the construction phase, the 3D design model with related engineering information is used to explain, assist, and verify on-site works[4]. BIM provides methods to represent construction information via shared 3D scenes, which can reduce misunderstanding and promote communication between project stakeholders. BIM is closely associated with several visual computing techniques, including modeling and visualization of 3D models, real-time 3D animations, mobile 3D interaction, as-built modeling, and 3D-2D synchronization. BIM has enabled the development of new construction approaches with high efficiency, and has provided many opportunities for applying computer technology to avoid redundant tasks in the traditional construction processes[5]. Meanwhile, vision-based processing and data mining are used to monitor construction sites and recognize key events automatically. While traditional approaches for monitoring construction site require manpower, cameras can help record the condition of construction sites more continuously. In addition to fixed cameras, drones and other movable devices can provide more comprehensive viewpoints. Meanwhile, real-time video processing and analysis approaches contribute to long-time monitoring and timely warning.

Although visual computing plays an essential role in construction, no bibliometric review has been provided to this day. Bibliometric methods are exhaustive and useful in analyzing all academic works in a given area[6]. Tools supporting bibliometric analysis and visualization based on reliable scientific literature sources, such as the Web of Science, Scopus, and Google Scholar, have been proposed and used for scientific review[7]. CiteSpace[8], VOSviewer[9], and SCI2[10] are tools typically used for graph visualization, highlighting not only the potential patterns but also the scientific changes.

In order to discover the development path of the knowledge body of visual computing in construction, this study uses bibliometric tools to analyze the relevant literature with citation information. Based on the results, a further explanation of the scientific changes are proposed to highlight the contributors, their influences, main topics, and trends. This study aims to comprehensively dissect the research work on visual computing in construction, to help locating the critical knowledge

and to indicate the recent trends and potentials to guide future investigations in this area.

2. Methodology

This study conducts a three-step bibliometric analysis of the research works in the area of visual computing in construction, as shown in Fig 1. The first step is data preparation. In this step, a search strategy with different keywords is applied to obtain literatures and their details for bibliometric analysis. Based on the data collected in the first step, the research history and trends of the field are analyzed. CiteSpace is an evolving software for a systematic review of research fields[7] as it is one of the few bibliometric tools that support timeline analysis, we choose it to generate the landscape co-citation network and the timeline view for trends analysis. By using CiteSpace, we generate and analyze the landscape view and clusters in the second and third steps. After the three-step bibliometric analysis, this study discusses the results and draws conclusions that will contribute to the body of knowledge.
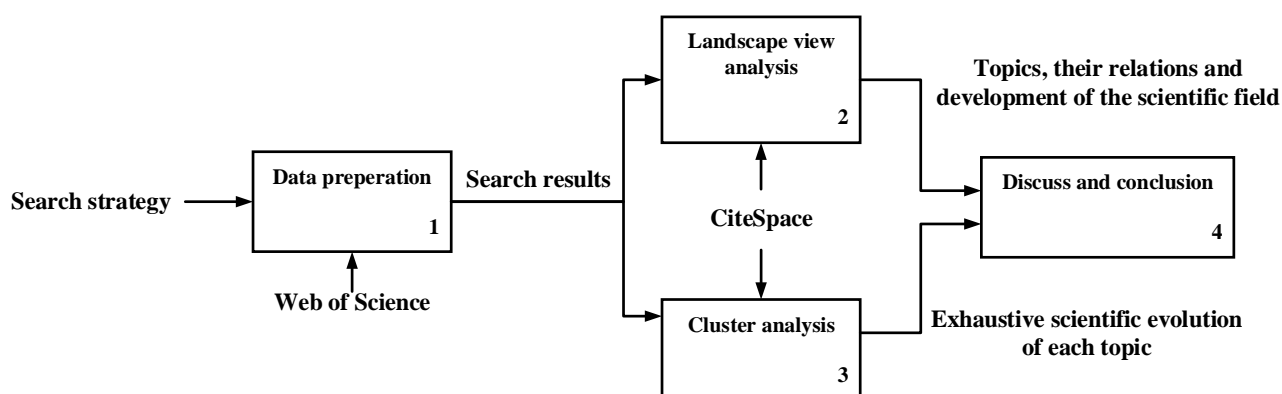

Fig 1 IDEF0 diagram for the process of this study

3. Bibliometric analysis

3.1. Data preparing

Visual computing is a broad scientific area that includes multiple disciplines and research topics, such as computer graphics, image and video processing, 3D visualization, and virtual and augmented reality (AR)[11]. Laser scanning and 3D modeling are also key topics, especially in construction. This study chooses the Web of Science as the literature source to ensure the quality of the collected literatures. The search strategy is shown in Fig 2.

Fig 2 Search strategy used for searching database of Web of Science

The word visual computing is so broad and it is not directly used in most of the published papers. Therefore, several key research topics in visual computing are used in the search strategy of this study. This search was conducted on November 24, 2019. With the timespan not specified, it captures 1315 results. And all the results are used in the analysis and the conclusions drawn from it.

3.2. Landscape views

A landscape view of the co-citation network obtained from the search results, for the period 1996-2019, is shown in Fig 3. A clustered co-citation network shows the influence of each published work, their citation relationships, and their correlations. In the graph, the node colors show the influence of the published works. The warm colors (e.g., red) indicate a recent influence, and the cold colors (e.g., blue and gray) indicate an older influence. In Fig 3, nine clusters are detected by keywords and labeled. Among them, cluster #4 and #6 are at the central position, indicating that these studies have a strong connection with others. Moreover, the node colors have a relatively concentrated distribution, indicating the fast evolution of knowledge.

To briefly show the development history of each cluster, we generate a timeline view shown in Fig 4. In the timeline view, the position of the nodes in the timeline refers to the publishing year. Although our search scope contains the year 2019, the works published in 2019 are not contained in Fig 4, because they have not been cited yet. Three types of clusters could be identified. The first type includes cluster #0. The main feature of this type is that the publishing years of nodes are relatively old, and the colors of nodes are mainly cold, which indicates that the publications associated with this type of cluster have almost no effect in recent years. The second type of cluster includes cluster #1, #2, #3, and #4. The main feature of this type is that a large number of nodes have a significant impact, and most of them are still important in recent years. The third type includes cluster #5, #6, #7, and #8. In this type of cluster, works have been published recently and it seems they would have a continuous influence on the research directions.
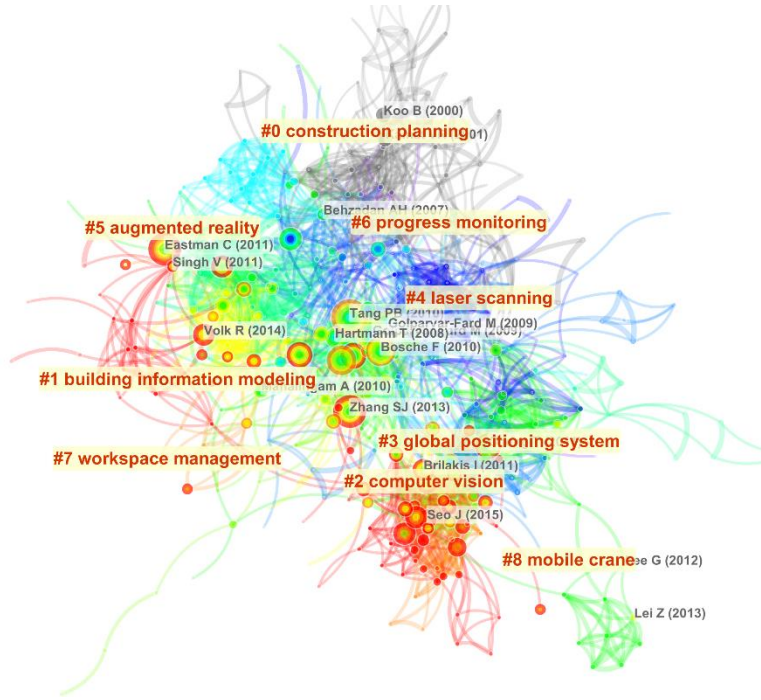
Fig 3 A landscape view of the co-citation network
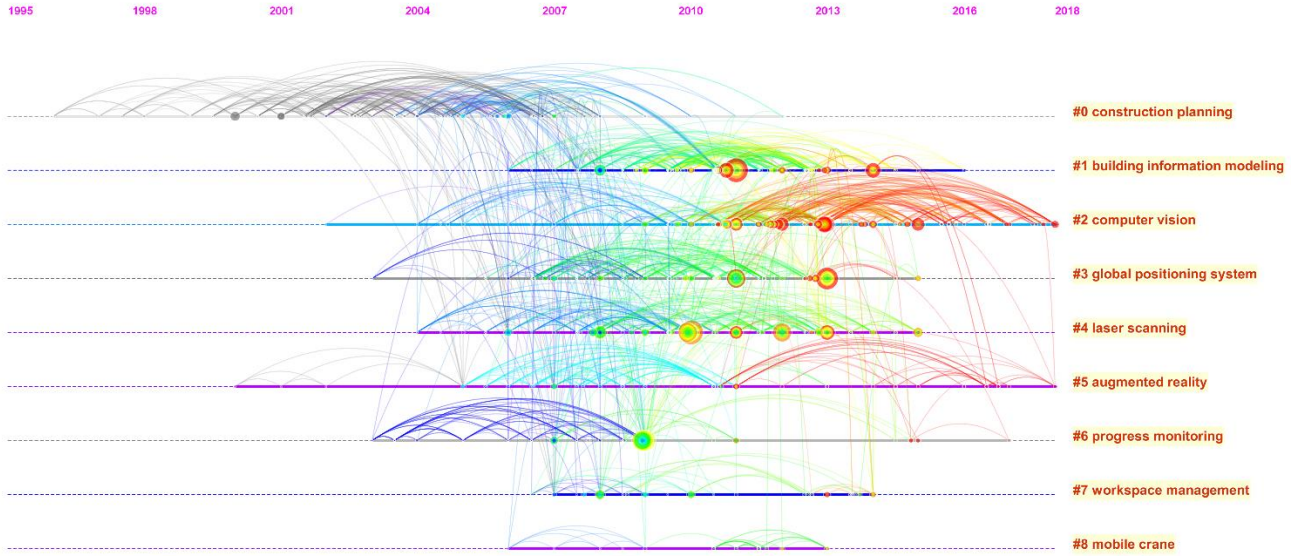
Fig 4 The landscape timeline view of the co-citation network

The research interests are changing continuously and some works have a significant influence on the changing of directions. We list the top 36 works with citation bursts of at least four years in Fig 5. The reference with the largest strength was proposed by Kamat and Martinez[12]. This paper emphasizes the importance of 3D visualization of the construction operation simulation and implements the first prototype system. The most recent burst references include the works of building information modeling (BIM) [13,14] and the works of computer vision-based recognition and tracking[15-18]. This result demonstrates that BIM and computer vision are gaining burst attention in these years, which is consistent with the results presented in Fig 4. specifically, one of the mentioned BIM-related works is the second edition of the BIM

handbook, and the other one is a literature review of BIM. They summarized the application and research directions of BIM, and provide a guideline for new researchers. While the burst works of computer vision mostly concentrate on some specific techniques, i.e., object recognition. The different results of the two above-mentioned research topics indicate that they have different burst reasons. In the section of research topic analysis, these reasons are revealed by a detailed analysis of the cluster data.
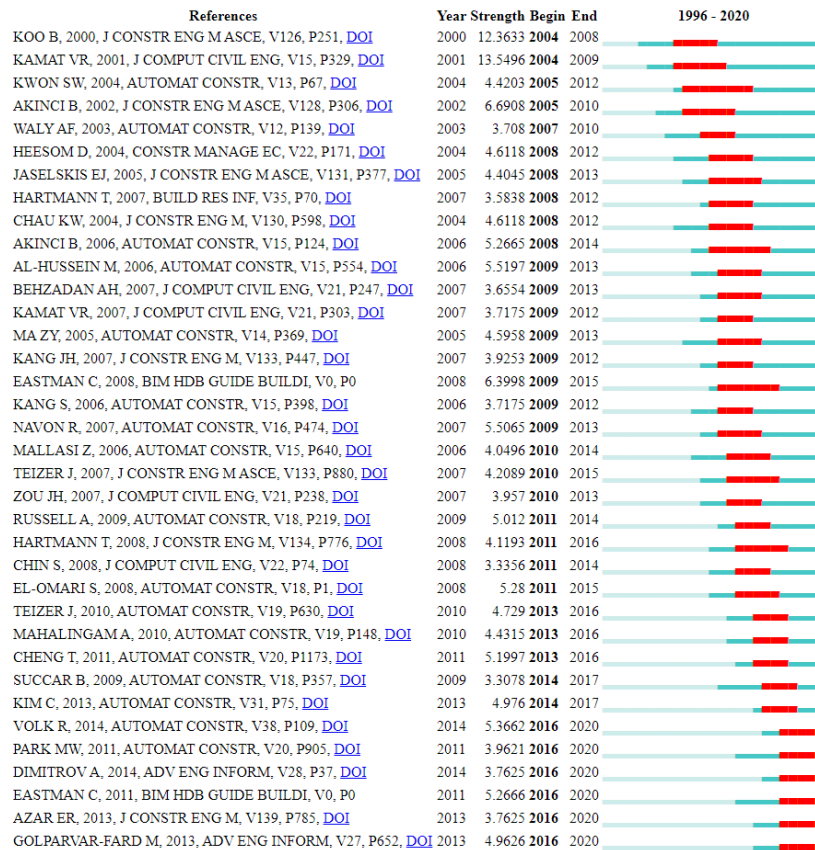
References	Year	Strength	Begin	End	1996 - 2020
KOO B, 2000, J CONSTR ENG M ASCE, V126, P251, DOI	2000	12.3633	2004	2008	
KAMAT VR, 2001, J COMPUT CIVIL ENG, V15, P329, DOI	2001	13.5496	2004	2009	
KWON SW, 2004, AUTOMAT CONSTR, V13, P67, DOI	2004	4.4203	2005	2012	
AKINCI B, 2002, J CONSTR ENG M ASCE, V128, P306, DOI	2002	6.6908	2005	2010	
WALY AF, 2003, AUTOMAT CONSTR, V12, P139, DOI	2003	3.708	2007	2010	
HEESOM D, 2004, CONSTR MANAGE EC, V22, P171, DOI	2004	4.6118	2008	2012	
JASELSKIS EJ, 2005, J CONSTR ENG M ASCE, V131, P377, DOI	2005	4.4045	2008	2013	
HARTMANN T, 2007, BUILD RES INF, V35, P70, DOI	2007	3.5838	2008	2012	
CHAU KW, 2004, J CONSTR ENG M, V130, P598, DOI	2004	4.6118	2008	2012	
AKINCI B, 2006, AUTOMAT CONSTR, V15, P124, DOI	2006	5.2665	2008	2014	
AL-HUSSEIN M, 2006, AUTOMAT CONSTR, V15, P554, DOI	2006	5.5197	2009	2013	
BEHZADAN AH, 2007, J COMPUT CIVIL ENG, V21, P247, DOI	2007	3.6554	2009	2013	
KAMAT VR, 2007, J COMPUT CIVIL ENG, V21, P303, DOI	2007	3.7175	2009	2012	
MA ZY, 2005, AUTOMAT CONSTR, V14, P369, DOI	2005	4.5958	2009	2013	
KANG JH, 2007, J CONSTR ENG M, V133, P447, DOI	2007	3.9253	2009	2012	
EASTMAN C, 2008, BIM HDB GUIDE BUILDI, V0, P0	2008	6.3998	2009	2015	
KANG S, 2006, AUTOMAT CONSTR, V15, P398, DOI	2006	3.7175	2009	2012	
NAVON R, 2007, AUTOMAT CONSTR, V16, P474, DOI	2007	5.5065	2009	2013	
MALLASI Z, 2006, AUTOMAT CONSTR, V15, P640, DOI	2006	4.0496	2010	2014	
TEIZER J, 2007, J CONSTR ENG M ASCE, V133, P880, DOI	2007	4.2089	2010	2015	
ZOU JH, 2007, J COMPUT CIVIL ENG, V21, P238, DOI	2007	3.957	2010	2013	
RUSSELL A, 2009, AUTOMAT CONSTR, V18, P219, DOI	2009	5.012	2011	2014	
HARTMANN T, 2008, J CONSTR ENG M, V134, P776, DOI	2008	4.1193	2011	2016	
CHIN S, 2008, J COMPUT CIVIL ENG, V22, P74, DOI	2008	3.3356	2011	2014	
EL-OMARI S, 2008, AUTOMAT CONSTR, V18, P1, DOI	2008	5.28	2011	2015	
TEIZER J, 2010, AUTOMAT CONSTR, V19, P630, DOI	2010	4.729	2013	2016	
MAHALINGAM A, 2010, AUTOMAT CONSTR, V19, P148, DOI	2010	4.4315	2013	2016	
CHENG T, 2011, AUTOMAT CONSTR, V20, P1173, DOI	2011	5.1997	2013	2016	
SUCCAR B, 2009, AUTOMAT CONSTR, V18, P357, DOI	2009	3.3078	2014	2017	
KIM C, 2013, AUTOMAT CONSTR, V31, P75, DOI	2013	4.976	2014	2017	
VOLK R, 2014, AUTOMAT CONSTR, V38, P109, DOI	2014	5.3662	2016	2020	
PARK MW, 2011, AUTOMAT CONSTR, V20, P905, DOI	2011	3.9621	2016	2020	
DIMITROV A, 2014, ADV ENG INFORM, V28, P37, DOI	2014	3.7625	2016	2020	
EASTMAN C, 2011, BIM HDB GUIDE BUILDI, V0, P0	2011	5.2666	2016	2020	
AZAR ER, 2013, J CONSTR ENG M, V139, P785, DOI	2013	3.7625	2016	2020	
GOLPARVAR-FARD M, 2013, ADV ENG INFORM, V27, P652, DOI	2013	4.9626	2016	2020	

Fig 5 Top 36 burst references with citation bursts in at least four years

3.3. Research topic analysis

In the topic analysis, we start with topic number 1, which corresponds to cluster #0. Each topic has a label suggested by CiteSpace based on the log-likelihood ratio. In some cases, the suggested labels cannot represent the key topic properly. Therefore, before a detailed analysis, we use only the topic number. Despite the research topics being clustered, some of them have apparent citation relationships. When considering a number of citations over ten as a criterion to define significant relationship, we can find ten significant relationships, as shown in Fig 6. The label of topic 1 is construction planning. The core technique of topic 1 is 3D CAD. The relationship between topic 1 and topic 2 illustrates that BIM is used to support construction planning as 3D CAD does. Topic 1 and topic 2 are both related to topic 5 and topic 8 because workspace management and laser scanning are both related to construction planning, 3D modeling, and building

information. A significant difference between topic 5 and topic 8 is that laser scanning supports as-built 3D modeling, but workspace management uses scheduling data and building information. Topic 1 also has significant citation relationships with topic 6 and topic 4, showing that augmented reality and positioning techniques can support construction planning. Construction safety is the main problem mentioned in topic 4. Topic 4 is related to topic 5 and topic 3, reflecting that laser scanning and computer vision support construction safety. Topic 7 only has a significant relationship with topic 5, indicating that laser scanning is usually used for progress monitoring recently.
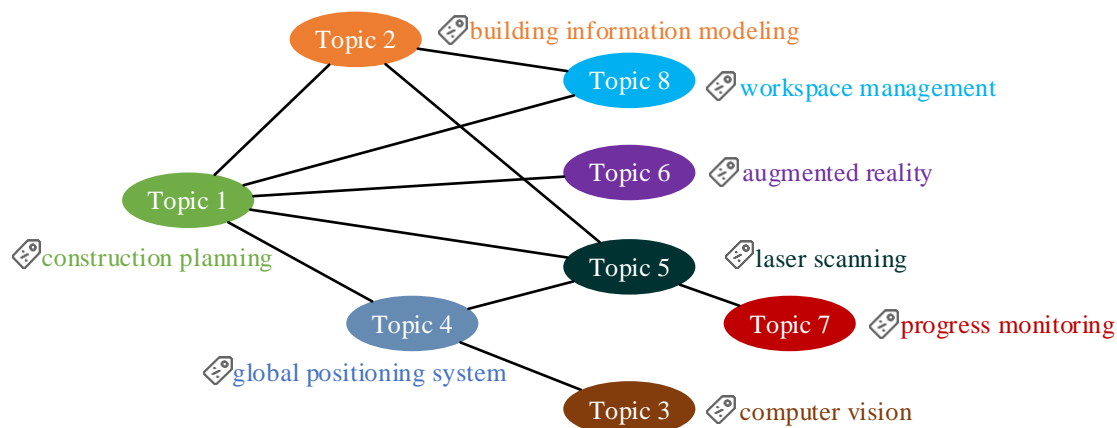
Fig 6 Significant citation relationships between topics

Meanwhile, Fig 4 shows that works related to topic 1 have the highest citation number among all topics. Topic 3, 4, and 9 are the most closed topics in the searching view of this study.

3.3.1. Topic 1: construction planning

The label of topic 1 is construction planning. It indicates the research direction in most cases. In the cluster of this topic, the top two cited works include the feasibility research of 4D CAD in commercial construction[19] and an approach enabling animated construction operations in 3D[12]. These two works illustrate that this topic concentrates on showing the construction progress in an animated 3D scene. Other typical works include integrating 3D visualization and simulation for tower crane operations[20], visualization of crane erection processes[21], 4D application for site layout and management[22], workspace analysis utilizing 4D visualization[23] and construction processes simulation systems[24]. The common purpose of all these works is to help people understand the construction process by simulating it in an intuitive scene. Fig 7 shows the timeline view of topic 1 with representative contributors. After 2010, it is hard to find more works in this cluster. The main reason could be that BIM replaced 3D CAD. BIM supports not only 3D modeling, like 3D CAD does, but also integrating project information in the entire project life-cycle. The timeline view of topic 2 (Fig 9) shows that BIM became a research topic in this scientific field in 2007. After that, 3D CAD was gradually less mentioned.
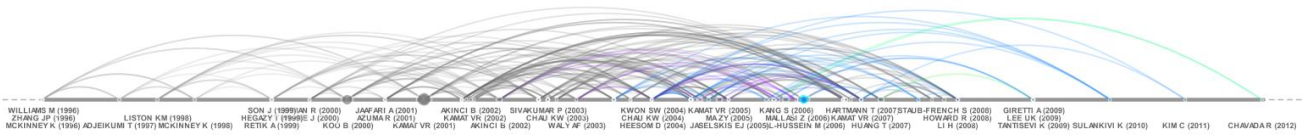
Fig 7 Timeline view of topic 1

Fig 8 illustrates the foam tree of keywords in topic 1. The figure indicates that it focuses on 4D site management and schedule management. The techniques used in the cluster include 4D computer-aided design (CAD), AR, and virtual reality (VR). They are used for simulation and animation to engage in construction control.
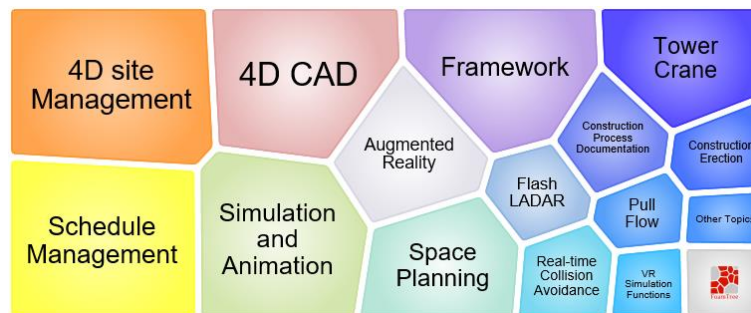

Fig 8 Foam tree view of keywords in topic 1

3.3.2. Topic 2: building information modeling

Topic 2 is labeled as building information modeling. When concentrating on the most cited works, we can pick out the core concept of this topic. The most cited work is the second edition of the BIM handbook[14]. It was published in 2011 and has 51 citations in all the collected literatures. The second cited work is the literature review of BIM[13]. The two above-mentioned works are also the most recent bursts found in Section 3.2, indicating that these two works are both the most important and the most popular in recent years in the topic. While both works   focus on BIM, the BIM handbook introduces and explains how to use BIM, while the other work reviews the literature and suggests the future works on using BIM for existing buildings. Both works systematically describe BIM, in the same way as as the third and fourth cited works: an introduction of BIM[25] and the first edition of the BIM handbook[26].

Fig 9 shows that topic 2 started in 2006 when Fu et al. proposed an IFC model viewer to support the nD model application[27,28]. Afterward, related works in this topic can be classified according to the research purpose. Some works aim to solve the BIM application problems, including the information requirement research[29], analyzing how to adopt BIM in the AEC industry[30], and using BIM to support sustainable design[31] and construction[32]. Some other works aim to explain the drivers for using BIM, such as exploring how to measure the benefits of BIM[33] and analyzing the project benefits of BIM[3]. Meanwhile, some works aim to solve technical problems when using BIM, such as enhancing the information exchange process[34], information integration[35,36], spatial data analysis[37,38], and geometric

optimization[39]. Furthermore, some works aim to enhance construction using BIM and other techniques, such as assisting the construction defect management[40], monitoring building performance[41], improving the monitoring of construction supply chain[42], using BIM and 4D to solve structural conflict problems[43,44], and lean production management systems based on BIM[45].
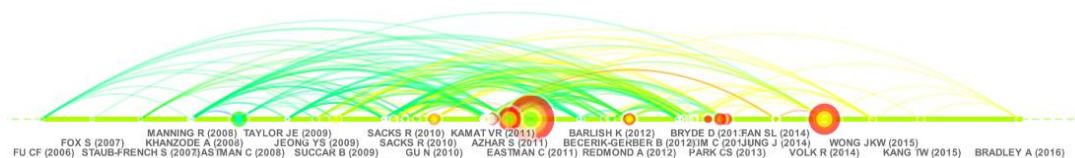

Fig 9 Timeline view of topic 2

According to Fig 10, BIM is mostly used to solve problems related to construction safety and management of the workspace. Four-dimension CAD and point clouds are always related to BIM. The results of BIM related works are mainly proposed framework, technique practice, and the literature review. In Fig 9, we can observe that topic 2 starts in 2007 and ends in 2016. The most active period is from 2008 to 2014. Although the citation of BIM bursts in recent years, the recent works are not classified in topic 2. Nowadays, similarly to other scientific fields, researchers in visual computing are not satisfied with the use of BIM only, but with quite a lot of new IT techniques.
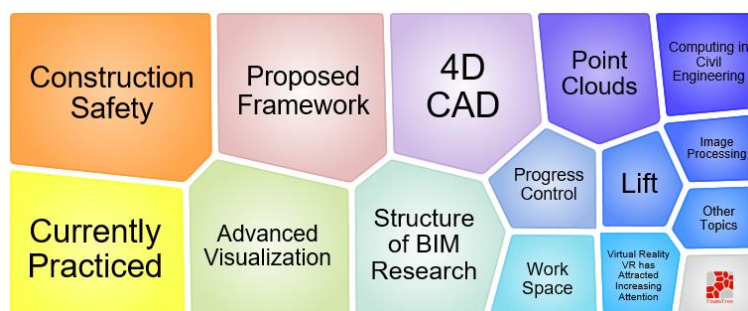

Fig 10 Foam tree view of keywords in topic 2

3.3.3. Topic 3: computer vision

This topic is using computer vision to capture and solve construction problems. Several directions appeared, including the automatic object recognition[46-52], automated vision tracking[18, 53-56], vision-based action recognition of specific construction equipment or workers[16,57-60], vision interpretation[61-63], and using computer vision for specific construction management purposes, such as construction safety and health monitoring[64,65], progress monitoring[17], and performance monitoring[66]. Also, some sensor techniques were used for monitoring workers' activities[67] or construction site status[68].

Fig 11 shows that topic 3 started in the early 2000s, but highly cited works appeared after 2010. Moreover, in recent years, highly efficient deep learning techniques have brought more possibilities for applying computer vision in

construction[60,69]. Owing to the development of vision-based computational techniques, construction site management has more opportunities to become more automatic and could acquire more real-time site information.

Fig 11 Timeline view of topic 3

According to Fig 12, main construction problems in this topic include safety training, resource tracking, construction equipment operations, risk assessment, project control, and crane lift. Besides, the core techniques related to this cluster are BIM, construction object recognition, equipment video analysis, and point cloud processing.

Fig 12 Foam tree view of keywords in topic 3

3.3.4. Topic 4: global positioning system

Although topic 4 is tagged as the global positioning system (GPS), the works related to this topic did not only use GPS. It is not clustered well and has two different research directions: location tracking[70,71] and construction safety[72-75]. Two significantly influent works demonstrate these two directions. The first one uses the ultra-wideband (UWB) for construction resource location tracking[76]. The second one uses BIM for automatic construction safety checking[77]. Additionally, some works use construction site positioning techniques for construction safety[78,79].

Despite presenting two works with significantly high quality, this topic developed more slowly after 2013, as shown in Fig 13. two of the three works cited in 2015 are authored by Sijie Zhang[77].
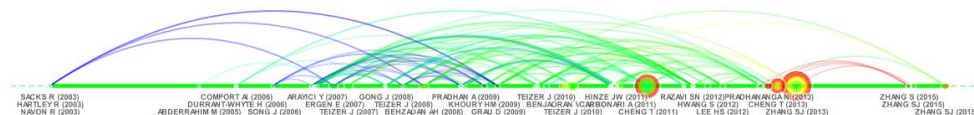

Fig 13 Timeline view of topic 4

Fig 14 shows that unlike positioning techniques, 4D BIM, VR, image matching, workspace analysis, and 2D video analysis are commonly used for resource tracking and safety management. Moreover, operation of tower cranes, blind spots of construction equipment, education and training related to safety management are the key topics in this cluster.

Fig 14 Foam tree view of keywords in topic 4

3.3.5. Topic 5: laser scanning

The core technique of topic 5 is laser scanning, the most common keywords used in related works. Such works contribute to reconstruction of 3D model from laser-scanned point clouds[80-85], performance analysis of laser scanning[86], and laser scanning for automatic progress tracking[87-89] or quality control[90,91], or both[92]. Fig 15 shows that this topic started in 2004, and slowly developed for nearly five years. In the 2010s, the cluster gained several frequently cited works which have had a continuous influence until today. However, similarly to topic 4, no more works with high impact appeared after 2015.
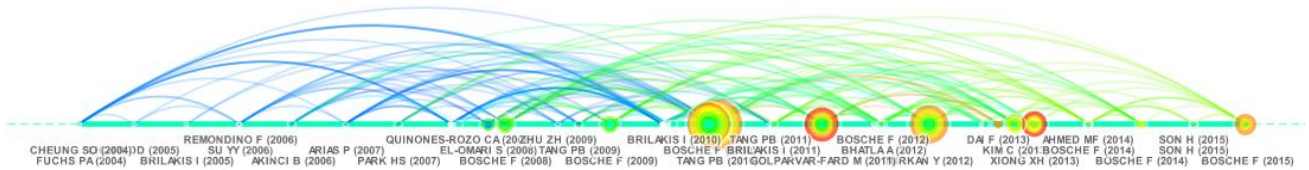

Fig 15 Timeline view of topic 5

According to Fig 16, point clouds generated by laser scanning can be applied to the construction of videos and digital images. As a result, nD CAD or BIM models could be dynamically updated with such kind of technology. Moreover, the most frequent purposes for using laser scanning are progress tracking and monitoring equipment operations.

Fig 16 Foam tree view of keywords in topic 5

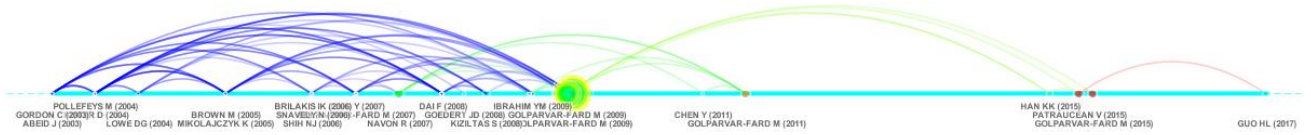### 3.3.6. Topic 6: augmented reality

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AR is well known and has been applied in various engineering fields, including construction. According to Fig 17, cluster #5 can be divided into three periods. The first is ranging from 2000 to 2005. In this period, it was attempted to apply AR to the architecture, engineering, and construction (AEC) industry. In 2005, Philip S Dunston and Xiangyu Wang[93] proposed a mixed reality (MR)-based visualization interface for the AEC industry, and cluster #5 stepped into a new period. In 2011, Vishal Singh et al.[94] proposed a BIM-based system framework for collaboration. Since then, AR was applied with BIM in construction. It is noteworthy that Cobo et al.[95] published a review of science mapping tools in 2011 and was cited by eight works in this topic. Most of the citing works are bibliometric reviews and data research of BIM. Additionally, laser scanning is also covered. Thus, AR is not the only technique in the topic, especially in the third period, since 2011 until now.

Fig 17 Timeline view of topic 6

Fig 18 indicates why and how to explore the benefits of using AR in construction. Cloud computing, radio frequency identification, BIM, and motion tracking are also introduced with AR for guiding the assembly process and construction education. It is worth mentioning that due to lower equipment costs and easier application approaches, mobile AR makes more sense than traditional AR in construction[96].

Fig 18 Foam tree view of keywords in cluster #5

3.3.7. Topic 7: progress monitoring

Concepts similar to progress monitoring appears in several other topics, such as project control in topic 3 and progress tracking in topic 5. The top-cited work provided by Mani Golparvar-Fard et al.[97] represents the main research direction, which is gathering and using the progress information from visual data. Fig 19 illustrates that the most widely used progress monitoring approach is an integration of 4D simulation model and site photographs [97].

Fig 19 Timeline view of topic 7

Fig 20 shows that despite photography being used by the top-cited work, point cloud and video are also used for progress monitoring. Moreover, object recognition, 4D CAD, AR, and dense stereo matching are applied to build the real scene and measure the progress. Most of the works in this topic focus on assembly activities.
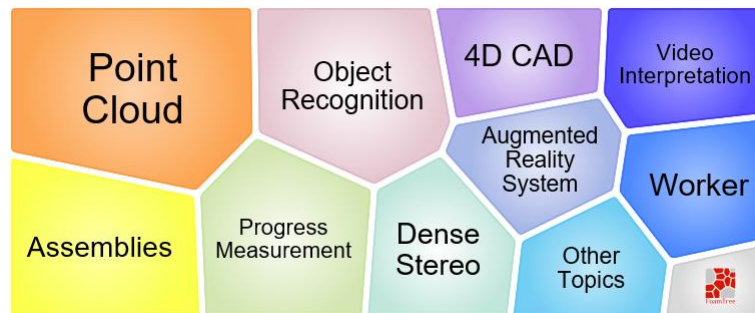

Fig 20 Foam tree view of keywords in topic 7

3.3.8. Topic 8: workspace management

According to Fig 21, topic 8 lasts for a short period, from 2007 to 2014. In this topic, 4D CAD[98-100] is the main technique for workspace management. Fig 22 shows that 4D CAD, 3D imaging, construction visualization, progress tracking, and integrating framework are used, demonstrating that workspace management is not the only research purpose. The space analysis approaches are also used in building operations, such as path planning[101].
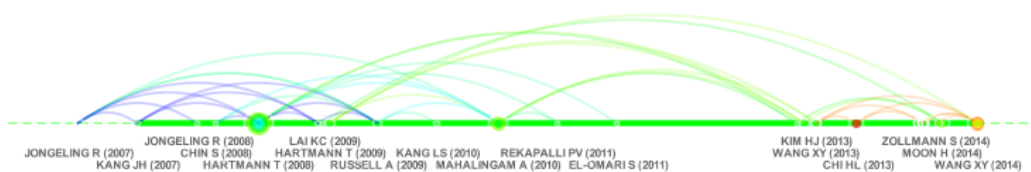
Fig 21 Timeline view of topic 8
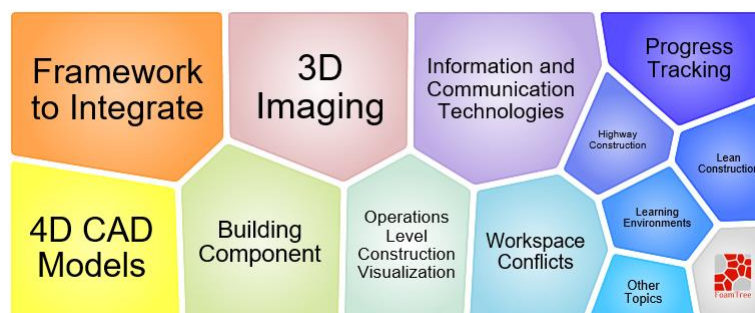
Fig 22 Foam tree view of keywords in topic 8

3.3.9. Topic 9: mobile crane

Topic 9 is from the cluster with the minimum size in the result. According to Fig 23, from 2006 to 2013, 14 works focused on solving problems such the heavy-lift problem, planning, coordination, and layout, when using a mobile crane on the construction site. However, compared to other clusters, this cluster attracts less research attention.
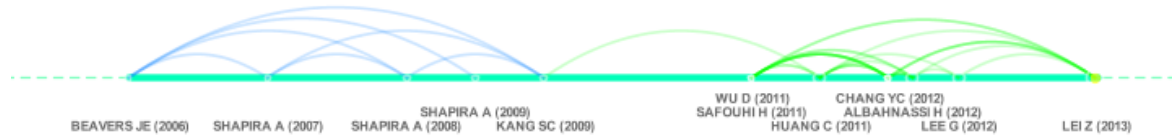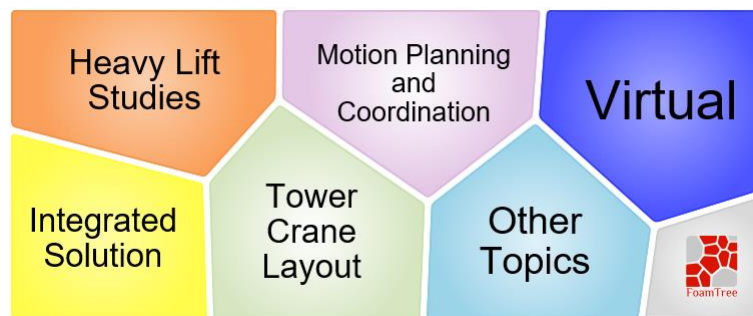

Fig 23 Timeline view of topic 9

Fig 24 Foam tree view of keywords in topic 9

4. Discussion

The nine topics presented in this study are the main research interests in the field of visual computing in construction. In the topic analysis, the development process, core research direction, and key works associated with each topic are revealed. Most of the suggested labels can represent the core concepts, except for topics 1, 3, and 7. Furthermore, most research topics of visual computing in the search strategy appear in the results, indicating that construction is an inclusive research area for visual computing. However, according to the results, most research directions have reached the bottleneck, including BIM, construction safety, laser scanning, and construction progress control. In recent years, most of the new works in these topics are rarely cited (no cited works after 2016 exactly). Meanwhile, some research topics have been gradually changed or replaced by new research directions, such as 4D CAD, workspace management, and mobile crane. These topics have few works with high attractiveness, and the works which were highly cited in the past have generated fewer citations in recent years.

Some significant findings are listed below:

Most problems related to 3D CAD have been solved and 3D CAD works as a basis in the construction area. No influential work has been published in the last five years in the research topic of 3D CAD, and few papers have cited works

on this topic recently. Nevertheless, 3D CAD has been the fundamental knowledge of other research topics. Three-dimension CAD provides the edition, storage, handling, and representation methods of 3D geometry information. Three-dimension-related research topics such as BIM, locating, laser scanning, AR, and workspace management frequently cite 3D CAD when they arose. Afterward, BIM gradually replaced 3D CAD as it was developed.

BIM lacks innovative and influential works in the field of visual computing. The developing path of BIM is promising, 15 published works that been cited over ten times (in the scope of this study) have been published. Meanwhile, some works related to BIM are classified in other topics, illustrating that it is highly adaptable. However, there have been hardly new highly cited works recently, while the top-cited works are still being cited. And it is suggested that combination of BIM and other visual computing techniques are interesting for future works.

Computer vision is not widely used and there is an increasing trend in the construction industry. Computer vision-related techniques are used to monitor, recognize, and track construction sites automatically. Additional topic analysis for topic 3 shows the most giant three subtopics in topic 3 are building information modeling, earthmoving machine, and deep learning. Around 2015, deep learning techniques stepped into a new stage. The improvement of the convolutional neural network[102,103], extreme learning machine[104], and other deep learning techniques[105] made it possible to recognize objects in image and vision data with high quality and efficiency. Construction site vision analysis techniques, including element and feature recognition, action recognition, vision tracking, vision interpretation, have been studied. Meanwhile, automatic vision processing made it possible to monitor construction safety, progress, and performance. Although some works contribute to the above-mentioned research directions, the improvement of deep learning brings more possibilities. Meanwhile, computer vision is thought to help improving construction monitoring in the future.

Quite a lot of new techniques emerges for object positioning, laser scanning, progress monitoring, safety management. Like BIM, these research topics have been investigated for a couple of years, and highly cited works have emerged. Though different techniques are adopted, the main problems remain the same, for example, object/worker positioning, progress tracking, and safety management are usually mentioned in many literatures. However, these problems still need further investigation and new methods in solving them are welcome.

The above-mentioned analysis results indicate the research trends of visual computing in construction. In this scientific field, computer vision should be the main research topic for the next few years. Despite that other research topics have not generated highly cited works in recent years, it is possible to look for new research directions based on the existing body of knowledge. The researchers working on these topics may also propose new research topics to overcome current scientific limitations.

5. Conclusion

This study aimed to review the literature of visual computing in construction to draw the developing history and provide trends for upcoming research works in this area. The conclusions of this article are as follows.

1. Three-dimension design data, point clouds, videos, and photos are primary visual data sources.

2. The topics include techniques of data gathering, handling, analysis, storing, and representation for construction demands such as safety control and schedule management.

3. Three-dimension CAD and BIM are core topics of 3D representation.

4. Most topics have been missing influential works in recent years.

5. Computer vision is suggested as a better topic to publish high-quality papers.

In this paper, the works with significant values are pointed out in each topic to provide a concise way to accumulate knowledge. The study has limitations due to the limited time of data collection and processing, and several potential research directions can be pursued:

1. The search strategy could be more accurate and have a broader coverage.

2. More literature databases and data cleaning techniques could be used to improve the search results.

3. The conclusion could be more convincing if other bibliometric tools and approaches were introduced.

4. It would be worth looking for better cluster results by introducing new bibliometric tools.

5. Topic 8 and topic 9 would be worth further studying, without limitation to this scientific field.

Declarations

Availability of supporting data

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Abbreviations

AEC: architecture, engineering, and construction

AR: augmented reality

BIM: building information modeling

CAD: computer-aided design

GPS: global positioning system

IFC: industry foundation classes

MR: mixed reality

UWB: ultra-wideband

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Jia-Rui Lin proposed the idea and designed the framework, Heng-Wei Wang collected the data, conducted preliminary data analysis and was a major contributor in writing the manuscript, Zhen-Zhong Hu analyzed and interpreted the data. All authors read and approved the final manuscript.

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40

References

[1]   Pouli T, Reinhard E, Cunningham DW (2013) Image statistics in visual computing. CRC Press, Boca Raton

[2]   Posada J, Toro C, Barandiaran I, Oyarzun D, Stricker D, De Amicis R, et al (2015) Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. IEEE Comput Graph Appl 35(2):26-40

[3]   Bryde D, Broquetas M, Volm JM (2013) The project benefits of Building Information Modelling (BIM). Int J Project Manage 31(7):971-980

[4]   Li NX, Li Q, Liu YS, Lu WL, Wang WQ (2020) BIMSeek++: retrieving BIM components using similarity measurement of attributes. Comput Ind 116:103186

[5]   Lin JR, Hu ZZ, Zhang JP, Yu FQ (2016) A natural‑language‑based approach to intelligent data retrieval and representation for cloud BIM. Comput‑Aided Civil Infrastruct Eng 31(1):18-33

[6]   Chen CM, Song M (2019) Visualizing a field of research: a methodology of systematic scientometric reviews. PLoS One 14(10):e0223994

[7]   Chen CM (2017) Science mapping: a systematic review of the literature. J Data Inf Sci 2(2):1-40. doi:10.1515/jdis-2017-0006**(请核对页码信息)**

[8]   Chen CM (2006) CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inf Sci Technol 57(3):359-377

[9]   van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84(2):523-538

[10] Zou X, Yue WL, Le Vu H (2018) Visualization and analysis of mapping knowledge domain of road safety studies. Accid Anal Prev 118:131-145

[11] (2020) Visual computing https://www.bath.ac.uk/projects/visual-computing/. Accessed 16 March 2020

[12] Kamat VR, Martinez JC (2001) Visualizing simulated construction operations in 3D. J Comput Civil Eng 15(4):329-337

[13] Volk R, Stengel J, Schultmann F (2014) Building Information Modeling (BIM) for existing buildings—Literature review and future needs. Automat Construct 38:109-127

[14] Eastman C, Teicholz P, Sacks R, Liston K (2011) BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd edn. John Wiley & Sons, New York

[15] Rezazadeh Azar E, Dickinson S, McCabe B (2012) Server-customer interaction tracker: computer vision–based system to estimate dirt-loading cycles. J Construct Eng Manage 139(7):785-794

[16] Golparvar-Fard M, Heydarian A, Niebles JC (2013) Vision-based action recognition of earthmoving equipment using

71   spatio-temporal features and support vector machine classifiers. Adv Eng Informat 27(4):652-663

72   [17] Dimitrov A, Golparvar-Fard M (2014) Vision-based material recognition for automated monitoring of construction

73   progress and generating building information modeling from unordered site image collections. Adv Eng Informat 28(1):37-

74   49

75   [18] Park MW, Makhmalbaf A, Brilakis I (2011) Comparative study of vision tracking methods for tracking of construction

76   site resources. Automat Construct 20(7):905-915

77   [19] Koo B, Fischer M (2000) Feasibility study of 4D CAD in commercial construction. J Construct Eng Manage

78   126(4):251-260

79   [20] Al-Hussein M, Niaz MA, Yu HT, Kim H (2006) Integrating 3D visualization and simulation for tower crane operations

80   on construction sites. Automat Construct 15(5):554-562

81   [21] Kang SC, Miranda E (2006) Planning and visualization for automated robotic crane erection processes in construction.

82   Automat Construct 15(4):398-414

83   [22] Ma ZY, Shen QP, Zhang JP (2005) Application of 4D for dynamic site layout and management of construction projects.

84   Automat Construct 14(3):369-381

85   [23] Mallasi Z (2006) Dynamic quantification and analysis of the construction workspace congestion utilising 4D

86   visualisation. Automat Construct 15(5):640-655

87   [24] Huang T, Kong CW, Guo HL, Baldwin A, Li H (2007) A virtual prototyping system for simulating construction

88   processes. Automat Construct 16(5):576-585

89   [25] Azhar S (2011) Building Information Modeling (BIM): trends, benefits, risks, and challenges for the AEC industry.

90   Leadership Manage Eng 11(3):241-252

91   [26] Eastman CM, Teicholz PM, Sacks R, Liston K (2008) BIM Handbook: a guide to building information modeling for

92   owners, managers, designers, engineers and contractors. Wiley, New York

93   [27] Fu CF, Aouad G, Lee A, Mashall-Ponting A, Wu S (2006) IFC model viewer to support nD model application.

94   Automat Construct 15(2):178-185

95   [28] Wang HW, Lin JR, Zhang JP (2020) Work package-based information modeling for resource-constrained scheduling

96   of construction projects. Automat Construct 109:102958

97   [29] Becerik-Gerber B, Jazizadeh F, Li N, Calis G (2011) Application areas and data requirements for BIM-enabled

98   facilities management. J Construct Eng Manage 138(3):431-442

99   [30] Gu N, London K (2010) Understanding and facilitating BIM adoption in the AEC industry. Automat Construct

100   19(8):988-999

101   [31] He TF, Zhang JP, Lin JR, Li YG (2018) Multiaspect similarity evaluation of BIM-based standard dwelling units for

102   residential design. J Comput Civil Eng 32(5):04018032

103   [32] Bynum P, Issa RRA, Olbina S (2013) Building information modeling in support of sustainable design and construction.

104   J Construct Eng Manage 139(1):24-34

105   [33] Barlish K, Sullivan K (2012) How to measure the benefits of BIM—A case study approach. Automat Construct

106   24:149-159

107   [34] Redmond A, Hore A, Alshawi M, West R (2012) Exploring how information exchanges can be enhanced through

108   Cloud BIM. Automat Construct 24:175-183

109   [35] Hu ZZ, Tian PL, Li SW, Zhang JP (2018) BIM-based integrated delivery technologies for intelligent MEP

110   management in the operation and maintenance phase. Adv Eng Softw 115:1-16

111   [36] Zhang JP, Liu Q, Hu ZZ, Lin JR, Yu FQ (2017) A multi-server information-sharing environment for cross-party

112   collaboration on a private cloud. Automat Construct 81:180-195

113   [37] Zhou YW, Hu ZZ, Lin JR, Zhang JP (2019) A review on 3D spatial data analytics for building information models.

114   Arch Comput Methods Eng. doi:10.1007/s11831-019-09356-6

115   [38] Lin YH, Liu YS, Gao G, Han XG, Lai CY, Gu M (2013) The IFC-based path planning for 3D indoor spaces. Adv Eng

116   Informat 27(2):189-205

117   [39] Hu ZZ, Yuan S, Benghi C, Zhang JP, Zhang XY, Li D, et al (2019) Geometric optimization of building information

118   models in MEP projects: algorithms and techniques for improving storage, transmission and display. Automat Construct

119   107:102941

120   [40] Park CS, Lee DY, Kwon OS, Wang XY (2013) A framework for proactive construction defect management using

121   BIM, augmented reality and ontology-based data collection template. Automat Construct 33:61-71

122   [41] Zhang YY, Kang K, Lin JR, Zhang JP, Zhang Y (2020) Building information modeling–based cyber-physical platform

123   for building performance monitoring. Int J Dis Sens Netw 16(2). doi:1550147720908170

124   [42] Irizarry J, Karan EP, Jalaei F (2013) Integrating BIM and GIS to improve the visual monitoring of construction supply

125   chain management. Automat Construct 31:241-254

126   [43] Zhang JP, Hu ZZ (2011) BIM-and 4D-based integrated solution of analysis and management for conflicts and

127   structural safety problems during construction: 1. Principles and methodologies. Automat Construct 20(2):155-166

128   [44] Hu ZZ, Zhang JP (2011) BIM-and 4D-based integrated solution of analysis and management for conflicts and

129   structural safety problems during construction: 2. Development and site trials. Automat Construct 20(2):167-180

130   [45] Sacks R, Radosavljevic M, Barak R (2010) Requirements for building information modeling based lean production

management systems for construction. Automat Construct 19(5):641-655

[46] Memarzadeh M, Golparvar-Fard M, Niebles JC (2013) Automated 2D detection of construction equipment and workers from site video streams using histograms of oriented gradients and colors. Automat Construct 32:24-37

[47] Park MW, Brilakis I (2012) Construction worker detection in video frames for initializing vision trackers. Automat Construct 28:15-25

[48] Chi S, Caldas CH (2011) Automated object identification using optical video cameras on construction sites. Comput-Aided Civil Infrastruct Eng 26(5):368-380

[49] Shan D, Shehata M, Badawy W (2011) Hard hat detection in video sequences based on face features, motion and color information. In: Abstracts of the 2011 3rd international conference on computer research and development, IEEE, Shanghai, pp 25-29

[50] Azar ER, McCabe B (2012) Automated visual recognition of dump trucks in construction videos. J Comput Civil Eng 26(6):769-781

[51] Fang Q, Li H, Luo XC, Ding LY, Luo HB, Rose TM, et al (2018) Detecting non-hardhat-use by a deep learning method from far -field surveillance videos. Automat Construct 85:1-9

[52] Ren SQ, He KM, Girshick R, Sun J (2017) Faster R-CNN: towards real-time object detection with region proposal networks. IEEE Trans Pattern Anal Mach Intel 39(6):1137-1149

[53] Brilakis I, Park MW, Jog G (2011) Automated vision tracking of project related entities. Adv Eng Inform 25(4):713-724

[54] Yang J, Arif O, Vela PA, Teizer J, Shi ZK (2010) Tracking multiple workers on construction sites using video cameras. Adv Eng Informat 24(4):428-434

[55] Park MW, Koch C, Brilakis I (2012) Three-dimensional tracking of construction resources using an on-site camera system. J Comput Civil Eng 26(4):541-549

[56] Teizer J, Vela PA (2009) Personnel tracking on construction sites using video cameras. Adv Eng Informat 23(4):452-462

[57] Ray SJ, Teizer J (2012) Real-time construction worker posture analysis for ergonomics training. Adv Eng Informat 26(2):439-455

[58] Han SU, Lee SH (2013) A vision-based motion capture and recognition framework for behavior-based safety management. Automat Construct 35:131-141

[59] Yang J, Vela P, Teizer J, Shi ZK (2014) Vision-based tower crane tracking for understanding construction activity. J

Comput Civil Eng 28(1):103-112

[60] Ding LY, Fang WL, Luo HB, Love PED, Zhong BT, Ouyang X (2018) A deep hybrid learning model to detect unsafe behavior: integrating convolution neural networks and long short-term memory. Automat Construct 86:118-124

[61] Gong J, Caldas CH (2011) An object recognition, tracking, and contextual reasoning-based video interpretation method for rapid productivity analysis of construction operations. Automat Construct 20(8):1211-1226

[62] Gong J, Caldas CH (2010) Computer vision-based video interpretation model for automated productivity analysis of construction operations. J Comput Civil Eng 24(3):252-263

[63] Azar ER, Dickinson S, McCabe B (2013) Server-customer interaction tracker: computer vision-based system to estimate dirt-loading cycles. J Construct Eng Manage 139(7):785-794

[64] Seo JO, Han SU, Lee SH, Kim H (2015) Computer vision techniques for construction safety and health monitoring. Adv Eng Informat 29(2):239-251

[65] Chi S, Caldas CH (2012) Image-based safety assessment: automated spatial safety risk identification of earthmoving and surface mining activities. J Construct Eng Manage 138(3):341-351

[66] Yang J, Park MW, Vela PA, Golparvar-Fard M (2015) Construction performance monitoring via still images, time-lapse photos, and video streams: now, tomorrow, and the future. Adv Eng Informat 29(2):211-224

[67] Cheng T, Teizer J, Migliaccio GC, Gatti UC (2013) Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data. Automat Construct 29:24-39

[68] Siebert S, Teizer J (2014) Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. Automat Construct 41:1-14

[69] Krizhevsky A, Sutskever I, Hinton GE (2017) ImageNet classification with deep convolutional neural networks. Commun ACM 60(6):84-90

[70] Behzadan AH, Aziz Z, Anumba CJ, Kamat VR (2008) Ubiquitous location tracking for context-specific information delivery on construction sites. Automat Construct 17(6):737-748

[71] Pradhananga N, Teizer J (2013) Automatic spatio-temporal analysis of construction site equipment operations using GPS data. Automat Construct 29:107-122

[72] Benjaoran V, Bhokha S (2010) An integrated safety management with construction management using 4D CAD model. Safety Sci 48(3):395-403

[73] Teizer J, Allread BS, Fullerton CE, Hinze J (2010) Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. Automat Construct 19(5):630-640

[74] Zhang SJ, Sulankivi K, Kiviniemi M, Romo I, Eastman CM, Teizer J (2015) BIM-based fall hazard identification and

191   prevention in construction safety planning. Safety Sci 72:31-45

192   [75] Lin JR, Zhang JP, Zhang XY, Hu ZZ (2019) Automating closed-loop structural safety management for bridge

193   construction through multisource data integration. Adv Eng Software 128:152-168

194   [76] Cheng T, Venugopal M, Teizer J, Vela P (2011) Performance evaluation of ultra wideband technology for construction

195   resource location tracking in harsh environments. Automat Construct 20(8):1173-1184

196   [77] Zhang SJ, Teizer J, Lee JK, Eastman CM, Venugopal M (2013) Building information modeling (BIM) and safety:

197   automatic safety checking of construction models and schedules. Automat Construct 29:183-195

198   [78] Cheng T, Teizer J (2013) Real-time resource location data collection and visualization technology for construction

199   safety and activity monitoring applications. Automat Construct 34:3-15

200   [79] Teizer J, Cheng T, Fang YH (2013) Location tracking and data visualization technology to advance construction

201   ironworkers' education and training in safety and productivity. Automat Construct 35:53-68

202   [80] Tang PB, Huber D, Akinci B, Lipman R, Lytle A (2010) Automatic reconstruction of as-built building information

203   models from laser-scanned point clouds: a review of related techniques. Automat Construct 19(7):829-843

204   [81] Bosché F (2010) Automated recognition of 3D CAD model objects in laser scans and calculation of as-built

205   dimensions for dimensional compliance control in construction. Adv Eng Informat 24(1):107-118

206   [82] Xiong XH, Adan A, Akinci B, Huber D (2013) Automatic creation of semantically rich 3D building models from laser

207   scanner data. Automat Construct 31:325-337

208   [83] Bosche F, Haas CT (2008) Automated retrieval of 3D CAD model objects in construction range images. Automat

209   Construct 17(4):499-512

210   [84] Bosche F, Haas CT, Akinci B (2009) Automated recognition of 3D CAD objects in site laser scans for project 3D

211   status visualization and performance control. J Comput Civil Eng 23(6):311-318

212   [85] Brilakis I, Lourakis M, Sacks R, Savarese S, Christodoulou S, Teizer J, et al (2010) Toward automated generation of

213   parametric BIMs based on hybrid video and laser scanning data. Adv Eng Informat 24(4):456-465

214   [86] Golparvar-Fard M, Bohn J, Teizer J, Savarese S, Peña-Mora F (2011) Evaluation of image-based modeling and laser

215   scanning accuracy for emerging automated performance monitoring techniques. Automat Construct 20(8):1143-1155

216   [87] Turkan Y, Bosche F, Haas CT, Haas R (2012) Automated progress tracking using 4D schedule and 3D sensing

217   technologies. Automat Construct 22:414-421

218   [88] El-Omari S, Moselhi O (2008) Integrating 3D laser scanning and photogrammetry for progress measurement of

219   construction work. Automat Construct 18(1):1-9

220   [89] Kim C, Son H, Kim C (2013) Automated construction progress measurement using a 4D building information model

221 and 3D data. Automat Construct 31:75-82

222 [90] Akinci B, Boukamp F, Gordon C, Huber D, Lyons C, Park K (2006) A formalism for utilization of sensor systems

223 and integrated project models for active construction quality control. Automat Construct 15(2):124-138

224 [91] Bosché F, Guillemet A, Turkan Y, Haas CT, Haas R (2014) Tracking the Built Status of MEP Works: assessing the

225 Value of a Scan-vs-BIM system. J Comput Civil Eng 28(4):05014004

226 [92] Bosché F, Ahmed M, Turkan Y, Haas CT, Haas R (2015) The value of integrating Scan-to-BIM and Scan-vs-BIM

227 techniques for construction monitoring using laser scanning and BIM: the case of cylindrical MEP components. Automat

228 Construct 49:201-213

229 [93] Dunston PS, Wang XY (2005) Mixed reality-based visualization interfaces for architecture, engineering, and

230 construction industry. J Construct Eng Manage131(12):1301-1309

231 [94] Singh V, Gu N, Wang XY (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform.

232 Automat Construct 20(2):134-144

233 [95] Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2011) Science mapping software tools: review, analysis,

234 and cooperative study among tools. J Am Soc Inf Sci Technol 62(7):1382-1402

235 [96] Lin JR, Cao J, Zhang JP, van Treeck C, Frisch J (2019) Visualization of indoor thermal environment on mobile devices

236 based on augmented reality and computational fluid dynamics. Automat Construct 103:26-40

237 [97] Golparvar-Fard M, Peña-Mora F, Arboleda CA, Lee SH (2009) Visualization of construction progress monitoring

238 with 4D simulation model overlaid on time-lapsed photographs. J Comput Civil Eng 23(6):391-404

239 [98] Mahalingam A, Kashyap R, Mahajan C (2010) An evaluation of the applicability of 4D CAD on construction projects.

240 Automat Construct 19(2):148-159

241 [99] Russell A, Staub-French S, Tran N, Wong W (2009) Visualizing high-rise building construction strategies using linear

242 scheduling and 4D CAD. Automat Construct 18(2):219-236

243 [100] Moon HS, Dawood N, Kang LS (2014) Development of workspace conflict visualization system using 4D object

244 of work schedule. Adv Eng Informat 28(1):50-65

245 [101] Peng Y, Li SW, Hu ZZ (2019) A self-learning dynamic path planning method for evacuation in large public

246 buildings based on neural networks. Neurocomputing 365:71-85

247 [102] Jia YQ, Shelhamer E, Donahue J, Karayev S, Long J, Girshick R, et al (2014) Caffe: convolutional architecture

248 for fast feature embedding. In: Proceedings of the 22nd ACM international conference on multimedia, ACM, Orlando, pp

249 675-678

250 [103] Vedaldi A, Lenc K (2015) MatConvNet: convolutional neural networks for MATLAB. In: Proceedings of the

251   23rd ACM international conference on Multimedia, ACM, Brisbane, pp 689-692

252   [104]   Tang JX, Deng CW, Huang GB (2016) Extreme learning machine for multilayer perceptron. IEEE Trans Neural

253   Networks Learn Syst 27(4):809-821

254   [105]   Dahl GE, Sainath TN, Hinton GE (2013) Improving deep neural networks for LVCSR using rectified linear units

255   and dropout. In: Proceedings of 2013 IEEE international conference on acoustics, speech and signal processing, IEEE,

256   Vancouver, pp 8609-8613

257

258