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AUGMENTED INTELLIGENCE IN BIM: THE FUTURE OF ARTIFICIAL INTELLIGENCE IN CONSTRUCTION

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ABSTRACT: *Construction industry has been revolutionized by the introduction of Building Information Modelling (BIM), opening the doors for greater automation and productivity across different stages of construction projects, from start to finish, which has improved coordination between stakeholders and has been instrumental in completing projects faster than ever before. Artificial intelligence (AI) is a revolution in the field of technology that has completely changed the way the world works. It has taken innovation to a whole new level with its capabilities reaching beyond imagination, that has raised concerns from human beings over its potential ability to take over humans. Augmented Intelligence (AuI) is a concept which is aimed at creating a human-AI partnership of equality, to improve efficiency and precision in decision-making and to control unchecked development of AI that can threaten the society. AuI enables humans and machines to deal effectively with the drawbacks of one another. Construction industry continues to be plagued with severe time, cost and productivity issues and innovation is crucial to overcome the challenges, where AuI can play a massive role to solve them. This study aims to highlight the potential benefits of the novel concept of AuI and existing literature on BIM-AI integration is reviewed to identify areas and extent of research in this field, to inspire future research and innovation, towards a promising future for the construction industry.*

KEYWORDS: *Augmented intelligence, BIM, Artificial intelligence (AI), Construction Industry*

1. INTRODUCTION

Building Informational Modelling (BIM), over the years, has evolved from being a simple visualization aid to a sophisticated system that is enabled to perform complex analysis for construction projects. Besides, it also plays an important role in asset management for the post-construction stage [1]. The evolution of BIM can be largely credited to the advancements in technology, thanks to 'Industry 4.0'. There has been a dramatic increase in BIM research in application of next-generation technologies like Artificial Intelligence (AI), Blockchain [2], Internet of Things (IoT), Cloud computing, Cybersecurity, Digital twin, 3D Printing, Big Data [3], Augmented Reality/Virtual Reality (AR/VR) [4], Unmanned Aerial Vehicles (UAV) [3] across the various uses of BIM.

Augmented Intelligence (AuI) is a relatively new concept which seeks to strike a balance between AI and humans, primarily aimed at resolving the existing tension between man and machine with growing fears of replacement of humans by machines, thanks to the fact that several people are expected to lose their jobs to AI, which has already started taking effect due to the disruption caused by Generative AI. Even though AI is expected to create millions of new jobs in the future [5], there remains an uncompounded fear and insecurity of being replaced. What AuI does is, it combines the capabilities of AI, like the ability to harness huge volumes of data, the iterative power of computers and pin-point accuracy, with the human capabilities to generalize and derive meaning from data in a way that is valuable for a particular concept, takes advantage of human creativity and most importantly, emotions, which will be extremely difficult for machines, to replicate the complexity of the interaction of human brain with neurochemicals that results in the creation of infinitesimally many emotions within a single human being. In short, the goal of conceptualizing AuI is to account for the shortfalls in machines and humans and to serve as a bridge of unity. Machines will assist humans instead of replacing them entirely.

This paper aims to discuss the potential benefits and challenges of bringing together two promising sectors – BIM and AuI, by reviewing recent studies and literature, in a quest to achieve greater automation and improvement in quality and cost objectives of the construction industry that can benefit all the stakeholders. Research on AuI in the construction industry is currently at a primitive stage. AuI is being widely viewed as a promising future with great potential, hence it is imperative for the construction industry to be in line with the latest technological trends that can bring about a much-needed revolution in the industry to cater to its growth and address the challenges faced by the industry.

2. BACKGROUND

2.1 Building Information Modelling (BIM)

BIM is a methodology to create and manage digital representations or models of various structural components of a building, which has also been adopted for creating digital models of infrastructure assets. These models contain useful data that can be extracted, processed, and shared with the various stakeholders, enabling a collaborative approach between various stakeholders in the construction industry for efficient decision-making. Organizations across the world have been utilizing BIM for planning, organizing, designing, construction, operation, and maintenance of various infrastructure projects, such as utilities pipeline network, communication networks, highways, bridges, ports, tunnels, and more. BIM plays a role to assist in the selection of most suitable options during design, construction and even for building demolition. Furthermore, BIM enables stakeholders in the industry to visualize the final deliverables in advance, much before the construction activities commence. BIM majorly contributes to reduction of construction waste and rework, facilitating projects to be completed within their designated timeframes, budget, and resource constraints. It is widely regarded as an information management tool which is essential for making timely decisions and to ensure sustainable planning and execution of construction projects. [6]

The concept of Level of Development (LoD) originated for BIM approach in a project, which required the extent of information needed to create a model to be determined in advance, for each component of the model to ensure its effective use in its intended context. The degree of information required to differentiate each conceptual model, upon which various BIM processes can rely, was recognized early in the evolution of BIM [7], due to the basic understanding that not all components of a structure require detailed modelling unless it has a structural significance. According to the American Institute of Architects (AIA), LoD is classified into the following levels, as shown in table 1:

Table 1: Level of development (LoD) in BIM [8]

Level of development (LoD)	Extent of Information	Description
LoD 100	Elementary	Conceptual model with basic information such as area and volume
LoD 200	Approximate	Approximate size, shape, quantity, location, and orientation
LoD 300	Accurate	Accurate size, shape, quantity, location, and orientation, representing a specific system

LoD 350	Accurate with external information	Specific system with its external environment
LoD 400	Constructable	Specific system with detailing, fabrication, installation, and assembly information
LoD 500	As-built	Field verified representation with complete details

Besides the level of detail, BIM models are also classified based on 'dimensions', which is a figurative description of capabilities in processing information [8]. While 3D BIM represents the model in three spatial dimensions, 4D adds the time aspect to the model, 5D adds cost and so on, which goes on till nth dimension. There is some disagreement about dimensions beyond 5D, but due to the growing focus on sustainability, energy analysis has been incorporated as sixth dimension in BIM models. [9]

BIM is employed for several purposes in the construction planning, design, and implementation phase, mainly for visualization, clash detection, lifecycle information management, reviewing design, structural analysis, quantity takeoff as well as for sunlight and environment analysis. Besides, it is also used for traffic flow simulation, computational fluid dynamics, crane operation simulation, virtual facility inspection, scheduling (4D) and cost estimation (5D). [11]

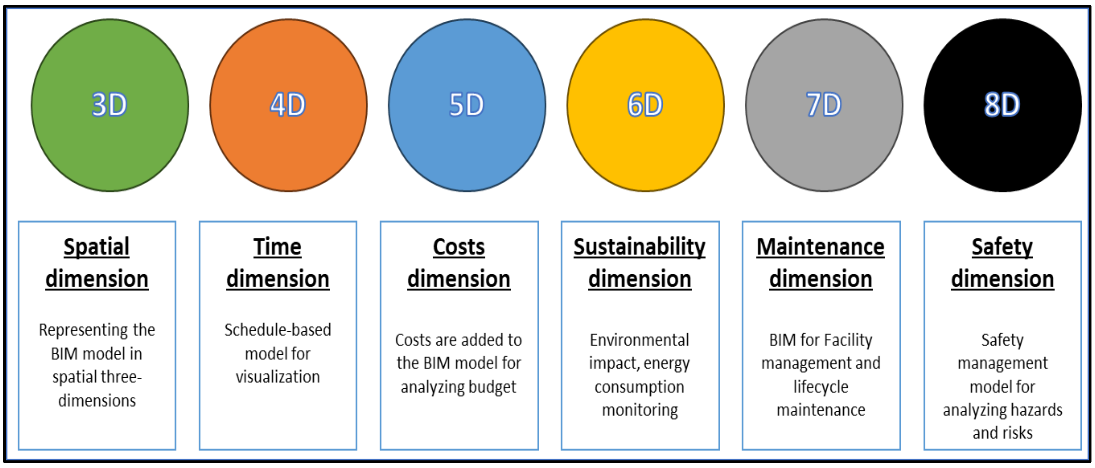


Figure 1. **Dimensions of BIM** [10]

2.2 Augmented Intelligence

Augmented Intelligence (AuI) has been defined as the collaborative alliance between humans and Artificial Intelligence (AI), which is aimed at boosting cognitive capabilities. These cognitive reinforcements encompass functions such as memory retention, decision-making and learning. As per the definition, AuI establishes a cooperative partnership with humans, by playing a supportive role in the decision-making process. This can be achieved by utilizing machine learning and deep learning algorithms to enhance human intelligence. [12]

The limited ability of human beings in perception and cognition can be overcome by AuI, that plays an assistive role in addressing the shortcomings of human nature. For instance, motor neurons in our nervous system deteriorate gradually and lose its functioning ability on aging. Furthermore, human capabilities can be constrained in exceptional circumstances, since the human body has its limits when dealing with extreme situations. Hence, there arises a need for technology to be leveraged in a way that can help us to surpass these limitations and to improve performance to a comparatively higher level than which has been achieved before. AuI provides a range of capabilities in this regard, which includes improved memory, computational abilities, and decision-making skills. [12]

While AI can replace human labour entirely, AuI concept will facilitate the development of AI algorithms which will enable humans to step in and override decisions made by the computer. [13]. This will bring an end to the perceived threat of humans being completely replaced by machines. AuI is being widely touted as the future of AI, towards making it a human-centric technology. The main objective of AuI is to develop, execute and implement AI technologies that places human values and preferences at the forefront. [14]

Machines excel in highly iterative processes involving large volumes of data, while human capabilities of common sense, judgment, creativity, and critical thinking cannot be replicated easily. AuI brings together the best of human and machine capabilities to enhance human behaviour in decision-making. [15] No matter how intelligent these technologies become, they cannot be as good as humans, who have evolved over millions of years to become extremely intelligent species, capable of even destroying their entire planet.

The technologies that power AI and AuI are essentially the same, the objectives, utilization and application context is fundamentally distinct. AI systems are designed to operate autonomously without the need for human interference. On the other hand, AuI harnesses AI to enhance human capabilities, which can surpass performance of individual humans or standalone AI systems in several important tasks. It is crucial to understand that AuI is not a new category of technology, instead, it represents a different approach to defining the purpose of AI technology. The pursuit of AI to explore its full potential is a commendable objective and its core technologies hold a great promise for the future, but the practical applications of AuI in the present world are likely to provide more significant benefits for the human society. [16]

AuI is also referred to as intelligence amplification, intelligence augmentation or cognitive augmentation, which makes it sound more friendlier than the frightening, job-destroying AI, for a better perception of this technology in the minds of people. Movies like *Star Trek* and *Terminator* have portrayed AI as a dehumanizing force with the potential to cause a disaster. But the truth is that the current capabilities of independent AI systems has not reached the ability to conquer the world [17]. Nevertheless, the concept of AuI, which is intended to keep the computing systems in check from unattended automation which may get out of control and cause harm to the society. The human-centric approach of AuI will address these concerns and help the focus to be directed towards increasing the power of assistive tools which can greatly improve outcomes of decisions taken by humans and provide them with valuable insights, while humans can spend more time on their creative ability, to come up with ideas that can be beneficial for mankind.

Since the concept revolves around human beings, as the most important stakeholder in AuI, it is important to understand certain aspects in the functioning of the human mind, which can be done through the concept of cognitive science. This branch of science explores the intricacies of human mind and the brain, delving into the representation and manipulation of knowledge in the brain, and understanding how mental processes manifest in the brain [18].

Cognitive scientists seek to unravel the computational processes that underlie cognitive functions by conceptualizing the mind as a theoretical computing device housed in the brain and examine how neural tissue brings these processes to life. This field has emerged at the intersection of diverse disciplines, and is significantly influenced by psychology, linguistics, computer science, and artificial intelligence, along with neurosciences, philosophy, and anthropology. Due to its eclectic roots, cognitive science embraces various perspectives and methodologies, which collectively aim to understand the structure of human intellectual functioning. [19]

Cognitive science explains the mechanism of human perception, learning and decision-making, and the enhancement of these capabilities is the primary objective for AuI. Usually, problem-solving is never done by humans on their own, instead, we coordinate with people and create teams to brainstorm a variety of perspectives and ideas when it comes to deciding on issues that are complicated. We have also been utilizing the latest developments in technology, starting from search engines to the most recently developed Generative AI, which aid in everyday managerial tasks. Cognitive scientists have increasingly focussed on the need to expand cognitive science, to develop a deeper understanding into intelligent systems comprising of human groups and human-machine teams, which will help to understand the true nature of their complex interactions, and thus will help us to work on areas where human capabilities can be improved. The pre-existing understanding of individual human cognition can be applied to these intelligent systems as cognitive systems to study their shared properties of cognition. For example, conversations, narratives, films, and gossips collectively serve the purpose of improving behaviour of individuals through lessons that can be learnt from other people's real or fictionalized experiences. This can be similarly modelled in machines using reinforced learning algorithms. The sole purpose of improving human-machine coordination rather than individual human or machine capabilities is to effectively deal with real-world problems in which the unique strengths of humans and AI can be leveraged to augment cognition and to create algorithms so that humans can interpret the reasoning of AI technologies, as well as to understand cognitive complementarity of humans and machines, to create powerful teams of humans and AI. [20]

Cognitive science relies on computational neuroscience to understand how cognitive models are implemented in the brain and to unearth the underlying algorithms. For instance, the models of sensory processing and object recognition are neural networks inspired by the brain, and their computations pose challenges at the cognitive level. The shared objectives of cognitive science and AI constructing task-performing models and reliance on common mathematical theory and programming environments has formed a synergy between the two and has propelled both the fields forward. Cognitive science guides AI in engineering of intelligence. The tasks undertaken by cognitive science can serve as a benchmark for AI systems, progressing from fundamental cognitive abilities to the pursuit of artificial general intelligence. Computational neuroscience provides algorithmic guidance for AI. The example of artificial neural networks (ANN), which was inspired by the human brain, is one of the AI fields that remains unrivalled across its several domains. By drawing inspiration from the neurobiological dynamical components and the overall functional layout of the human brain, we are set to witness several breakthroughs in AI technologies. Machine learning (ML) in AI optimizes statistical and computational efficiency, which remains a massive challenge in the era of big data. The human brain has been observed to integrate statistical and computational efficiency seamlessly, and understanding the algorithm of the brain presents an opportunity to enhance machine learning. [21]

2.3 Applications of AuI

The power of AuI lies in its ability to uncover the hidden potential of data and to unravel the complex patterns and correlations in the huge amounts of data that is generated every day, on a massive scale. AuI finds its application in a variety of fields like trading, sales, finance, healthcare, security, manufacturing, logistics and much more. [15]

In healthcare, several Deep Learning (DL) models have been developed for medical diagnosis and treatment. These models have performed exceptionally well, but are prone to errors. Fully automating the diagnosis and treatment processes can unintentionally cause issues in the procedure, which can sometimes be severe and is unacceptable in healthcare. With AuI technologies, the AI model will give healthcare practitioners the ability to efficiently analyze patient data and to make the most appropriate clinical decision. The combination of AI and the human mind of the clinician will help to achieve a high level of accuracy in medical prognosis. [22]. Besides, robotic surgery is another example of existing AuI technology that assists surgeons in being greatly precise and sensitive in medical surgeries.

The banking sector has also been transforming with the use of AI, aimed at making it more human-centric and to provide a highly personalized experience to the customers. Several major banks around the globe have launched chatbots to deal with the mainstream processes in banking. However, human touch cannot be replaced since the AI-based chatbots and virtual assistants cannot make precise judgement and are not sensitive enough to real world processes and human emotions. AuI will enhance decision-making capabilities of bankers through seamless large-scale data analysis to provide reliable banking services. [23]

Other examples for application of AuI include recommendation systems which analyze user information and behaviour by utilizing machine learning algorithms to provide customized preferences, used by video-streaming platforms like Netflix. Process automation driven by robotics in manufacturing industry and predictive analytics tools are also a few examples technologies that are fundamental of AuI. [12]

3. RESEARCH ON AI IN BIM

To comprehend and subsequently review the progress of AI-based development in BIM, several journal papers and research articles were reviewed, to determine the areas in which AI has been used and suggested for enhancing BIM. The reviewed literature was obtained by running searches in Google Scholar, Science Direct, T&F Online, Springer Link and Web of Science, among which publications having a SCImago Journal Ranking of either Q1 or Q2 were filtered and selected for literature review.

A related existing review paper studied research papers on integrated applications of AI techniques in BIM for publications from the year 2010 to 2020. Their findings mention classifying the mode of integration for the AI-BIM techniques into three categories, namely, accumulating and updating models, controlling and examining them, and executing the BIM-based tasks [24]. In this paper, the focus is on publications from 2020 to 2023 in integrated AI-BIM applications to understand the extent to which research has progressed in this field.

3.1 Literature search and screening

To gather and analyze data on extent of research in the last 10 years, an advanced search for publications was done using Web of Science (WoS) database, which was executed using the keywords ‘Machine Learning’, ‘Deep learning’, ‘Natural Language Processing’, ‘Robotics’, ‘Computer Vision’, ‘Expert Systems’ which are the main domains of AI. For the purpose of simplifying and to obtain a general overview of the field, more complicated AI terms were not used for the keyword search. WoS database was opted since it enables subscription-based access to several databases, especially the ones with the top academic journals. Only journal articles were selected due to their completeness and up-to-date information, and that these articles are peer-reviewed [24]. The comprehensive search query resulted as:

((TS= (BIM OR Building information modelling)) AND TS= (artificial intelligence* OR deep learning* OR machine learning* OR computer vision* OR robotics OR natural language processing* OR neural networks* OR expert systems*))*

In this advanced search, TS refers to the topic-based keyword, and Boolean operators AND, OR were used to enhance the search. Filters were set to ‘must include Building Information Modelling’ and language set to English, the year filter was set to 2013-2023 and resulted in 304 search results. Next, the results were filtered by journals for which the SCImago Journal Ranking (SJR) is either Q1 or Q2. The ranking indicates the prestige of a journal based on the number of citations. This refinement gave

192 search results. Further refining was done by going through the abstract of each of the articles to check whether they are relevant to the topic of AI applications in BIM, which gave 119 search results. These papers were further screened for their content and 54 papers were selected to be reviewed and discussed in this publication.

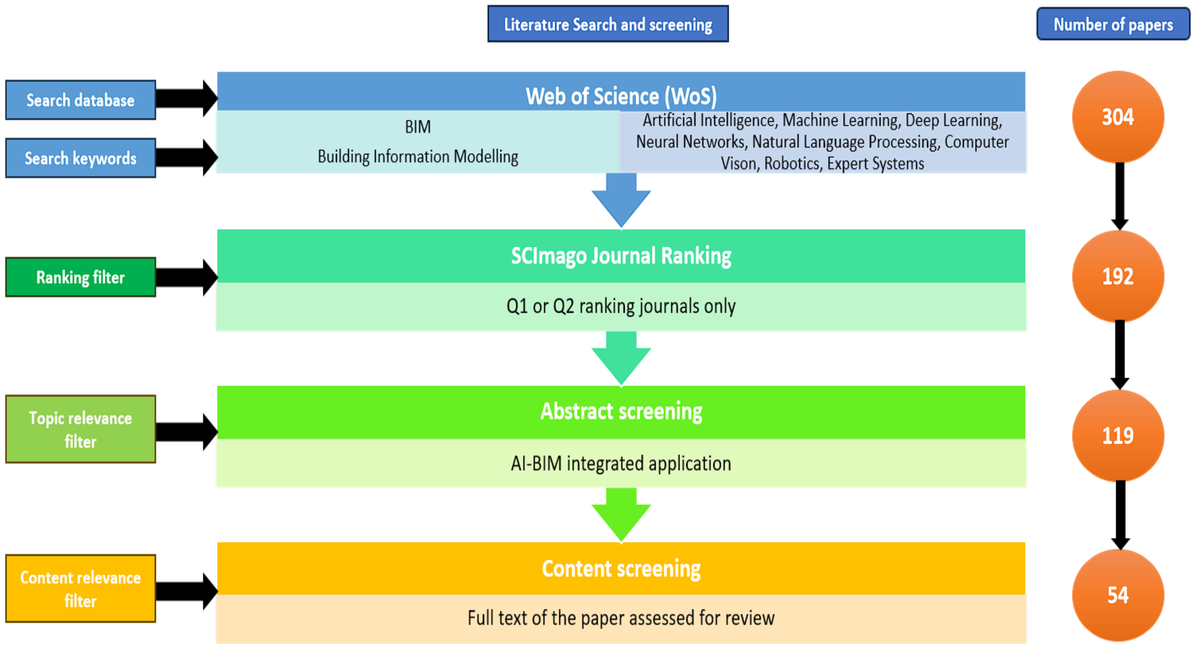


Figure 2. Literature search and screening process

3.2 Bibliometric analysis

3.2.1 Annual publication trend

The number of publications has consistently risen over the years, indicating increasing research in this field, the trend from 2020-23 (in Fig. 3) shows a similar increase but a steady rise indicating the progress in research has been somewhat slower. More research in the AI-BIM field can be expected in the coming years, thanks to the development of Generative AI and Large Language Models (LLM) (ChatGPT). A recent publication on developing an LLM-based virtual assistant indicates the strong potential for future research [25].

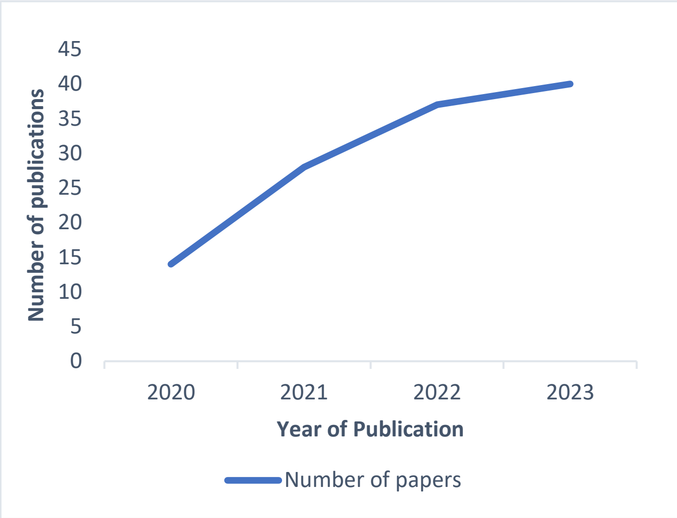


Figure 3. Publication trend for 2020-2023

3.2.2 Journal analysis

After the screening process, 119 articles were selected from 38 different journals. The summary of journals from which more than one paper were selected is shown in Table 2. Majority of the articles were selected from *Automation in Construction* (29%) and *Advanced Engineering Informatics* (8%). Remaining 63% of articles were chosen from 36 journals. The SCImago ranking indicates that only the topmost prestigious academic journals were referred for the literature review. The research field of the journals varies across disciplines like construction, computer science, electronics and mathematics, as listed in Table 2.

3.2.3 Publications by country

The articles were analyzed for their geographical area of publication, and it was inferred that most of the articles were published by researchers from the People's Republic of China (36%), followed by the United States of America (USA) (25%), Republic of Korea (South Korea) (12%) and Singapore (7%). These countries lead in technology-based research and is a testimony of their high economic growth and development in science and technology, which is shown in Figure 5.

Table 2. List of journals

Journal	**Number of Qualified publications**	**SCImago Journal Ranking**	**Publisher**
Automation in Construction	26	Q1	Elsevier
Advanced Engineering Informatics	10	Q1	Elsevier
Sensors	8	Q1	MDPI
Buildings	7	Q1	MDPI
Journal of Construction Engineering and Management	7	Q1	American Society of Civil Engineering (ASCE)
Journal of Computing in Civil Engineering	6	Q1	American Society of Civil Engineering (ASCE)
Energy and Buildings	4	Q1	Elsevier
Remote Sensing	4	Q1	MDPI
Sustainability	4	Q1	MDPI
Applied Sciences-Basel	3	Q1	MDPI
IEEE Access	3	Q1	Institute of Electrical and Electronics Engineers Inc. (IEEE)
Journal of Computational Design and Engineering	3	Q1	Oxford University Press
KSCE Journal of Civil Engineering	3	Q2	Korean Society of Civil Engineers
Building and Environment	2	Q1	Elsevier
Energies	2	Q1	MDPI
Engineering Construction and Architectural Management	2	Q1	Emerald Group
IEEE Transactions on Industrial Informatics	2	Q1	Institute of Electrical and Electronics Engineers Inc. (IEEE)
Journal of Building Engineering	2	Q1	Elsevier
Journal of Management in Engineering	2	Q1	American Society of Civil Engineering (ASCE)

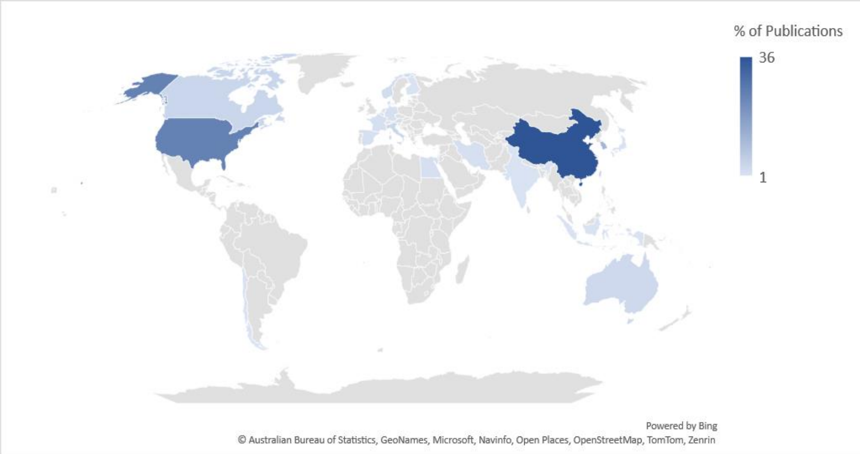


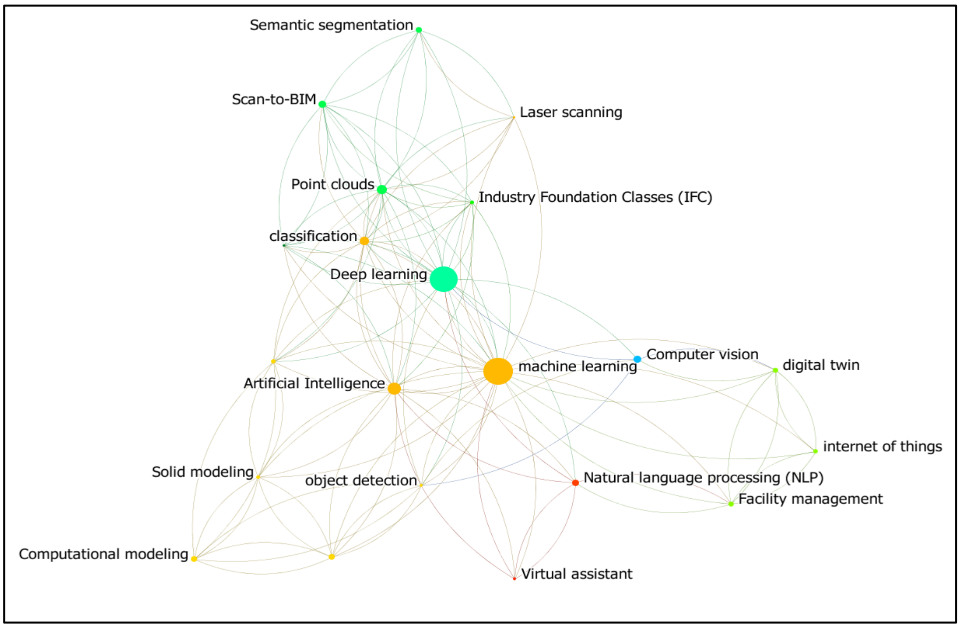
Figure 5. World map of research publications by country

3.2.4 Co-occurrence analysis

Bibliometric analysis through a network of keywords for the selected journal articles helps to recognize the pattern of common research areas [26]. Network links demonstrate the degree of congruence between the keywords and provides a visual representation the connectivity of the scientific areas of research. In other words, it assists in recognizing the primary areas of research in the field [27]. These keywords were automatically extracted using WoS for the selected articles, which gave 425 keywords from 119 articles. Similar keywords (for example, abbreviation of a terminology) were merged, and the keyword 'BIM' was not used since it is already known as the central topic of this research, but 'Artificial Intelligence' was retained for the analysis since there are several methods in AI. The co-occurrence network of the keywords was produced using a network analysis software called ORA-LITE, which was developed by the School of Computer Science, Carnegie Mellon University (CMU). The network consists of 425 nodes and 2758 links, with size of the nodes according to their degree centrality and coloured by Louvain method. To optimize the network overview, nodes with total degree of centrality above 13 are shown, which highlights the most commonly occurring keyword among the various articles.

This analysis highlights two different topics to which the keywords belong to, one refers to the AI systems and the other set of keywords belong to the trending topics in BIM-AI integration. Machine learning (ML) and Deep Learning (DL) are the most commonly occurring keywords which indicate that these technologies are at the centre of majority of research in this field. Technologies like Digital twin and Internet of Things (IoT) are being integrated with AI-BIM research to further enhance its capabilities. It also shows the co-occurrence of keywords belonging to BIM processes like Scan-to-BIM, point clouds, semantic segmentation, laser scanning etc., which are the key focus points for enhancement using AI. Industry Foundation Classes (IFC) is another key focus area for researchers, which is a file format that is most suitable for data interoperability in BIM, which is required for extraction of useful data from large number of files to create precise models.

Figure 6. Co-occurrence network analysis of keywords



4. FINDINGS

The findings after reviewing the selected relevant literature are summarized under the different AI methodologies adopted across various studies and their respective applications in BIM.

4.1 Machine Learning

4.1.1 Energy consumption

In a case study incorporating AI in BIM for analyzing energy consumption, ML has been implemented to automate the forecasting and optimization of building energy performance. This research suggests the creation of a BIM-based automated design system using smart algorithms with minimal human intervention for designing sustainable buildings. [28]. While optimizing building features such as lighting, natural ventilation, HVAC points etc., it is essential to maintain optimal level of thermal comfort inside the building. An investigative case study was carried out using several ML algorithms for this purpose [29]. These studies are aimed to automate design parameters for green buildings. To further enhance the process of automation in analyzing thermal comfort, a research case integrated BIM and ML with IoT devices, while also considering the experience of users in a real-world situation, to create a human-centric model [30]. This study highlights that while AI-based technologies can be used to automate several aspects in green building design, ultimately, it must cater to the occupants of the building, the human user. There is also an experimental study integrating BIM with ML algorithms capable of automating the process of designing eco-friendly public buildings [31].

4.1.2 Maintenance

BIM technology has revolutionized the field of Facility Management (FM) for maintenance of built assets. The application of AI in BIM-FM is to increase the accuracy of prediction for predictive maintenance, which can be done with the help of ML algorithms. IoT devices have also been incorporated in monitoring the status of MEP elements to obtain accurate information on maintenance requirements and the real-time data is analyzed by ML algorithms that aids in creating effective maintenance strategies [32]. In a research on reactive maintenance that is required to be carried out based on user complaints, ML models have been for qualitative classification of data to improve maintenance planning efficiency and used BIM for visualization of the maintenance process [33].

4.1.3 IFC

IFC has played a crucial role in automating several features in BIM, like verifying code compliance, simulations etc. A lot of unstructured information is generated which has to be processed by the BIM tools to enhance the decision-making process. Studies have been conducted on the usage of ML algorithms for semantic enrichment that assists in classification of spaces required for analyzing several parameters [34]. Semantic networks have also been created using graph theory and ML to connect unstructured information like text data to IFC, which is beneficial in the dynamic context of projects. Despite the use of ML algorithms, data quality issues like incomplete information or lack of understanding persist during classification of objects or spaces using IFC, which is a risk [35]. Research has been done on analyzing factors such as data quality, processing time and accuracy of prediction, to create a modified ML-based BIM classification system which takes into consideration the trade-offs between the factors to create more optimized algorithms and help to create precise models [36]. There are research studies also carried out to extend the application of IFC for automated real estate valuation using optimized ML algorithm and IFC-based data extraction from the BIM models, which provides an accurate and transparent method for property valuation [37]. 3D geometric deep neural networks algorithm in ML have been used for automated subtype categorization for door and wall elements instead of having to manually enter the details that may be erroneous [38]. A sparse residual Convolutional Neural Network (CNN) algorithm has been developed for IFC-centred semantic enrichment and classification of geometric elements [39].

ML techniques have also been applied for different phases of construction. A system for content recommendation in BIM has been developed for structural design and detailing that auto-suggests design elements based on user input drawings, which can result in significant time savings for designers, as well as it helps to improve accuracy in modelling [40]. Research work on creating an automated cost estimation tool using ML algorithms with MATLAB simulation has been done to facilitate complete automated quantity takeoff and cost estimation without the need for manual data entry and calculations [41]. Another remarkable prototype has been created in which advanced technologies of graphical processing, game engine, virtual reality and ML algorithms were integrated with BIM for project monitoring by comparing as-built models with the planned models, which assists in dealing with large volume of data generated during construction that can lead to incorrect understanding about the project's actual status [42].

4.1.4 Neural Networks

Neural networks are one of the most used ML algorithms and there are several studies on these algorithms utilized for enhancing BIM. An automated system has been conceived for continuous project monitoring using a CNN algorithm, assisted with DL-based semantic segmentation, which is capable of intelligently tracking construction progress with high accuracy [43]. In a research study, Graph Neural Network (GNN) algorithm is used for semantic enrichment for real-time construction progress monitoring using BIM that can detect occluded elements that may not be captured appropriately while creating as-built models [44]. The significant impact of BIM in construction projects has also been analyzed in a study on Public-Private Partnership projects by assessing Key Performance Indicators (KPI) using Copula Bayesian Network-based statistical analysis [45]. A neural network prediction model has been created to investigate the cost versus benefit trade-off in adopting BIM applications and selection of LoD for construction firms [46]. Research work on creating an energy consumption optimization technique with BIM and CNN has proven to be capable of generating a scheme to considerably reduce energy usage and increase natural lighting and ventilation [47].

4.2 Deep Learning

4.2.1 Point clouds

Most of the research on application of DL algorithms in BIM has been directed towards optimizing point cloud, which is one of the most important elements in model development. In a study on creating an automated workflow for generating point clouds with visual information for DL-powered semantic segmentation, by increasing the quantity of synthetic point clouds, they were able to improve segmentation and thus enable automatic remodelling in BIM [48]. Another research study proposed a 3D DL algorithm using LiDAR or RGB point clouds to automate semantically rich indoor BIM models with high precision and completeness [49]. Comparative study of image segmentation capability of models created with real and synthetic point clouds and a combination of the two, and the research showed a significant improvement in performance when few real cloud point datasets are augmented with synthetic point clouds, which can create building interior models that are unseen [50] Scan-to-BIM, the process in which laser scanners are used to record the dimensions of built environment and convert it into BIM models, has the tendency to faultily identify objects during the scan. An object verification methodology has been developed using DL algorithms on synthetic point clouds and actual scanned data for their accuracy in reconstruction [51]. Mechanical, Engineering and Plumbing (MEP) systems have increasingly adopted as-built BIM models for systematic management of these systems. Since most of these models are manually developed, a study was conducted on automating MEP systems modelling using 3D LiDAR scanners and advanced depth cameras to augment DL-based semantic segmentation, which were validated experimentally and found to be a reliable method for reconstructing models [52]. Another study on object classification in BIM using DL was done using an approach called Ensemble learning, where two DL-based AI models are assigned non-similar optimized weights to the results generated from the same data [53].

DL has also been used to address issues related to energy and the environment using BIM. A process has been created for complete automated checking of environmental regulatory compliance, by aligning semantic data in BIM with the stipulated computer-interpretable regulations using DL algorithms, that helps to deal with ambiguity in compliance checking [54]. Digital Twin (DT) from BIM model of an existing building has been developed, and a real-world environmental satisfaction analysis was conducted along with residents of the building, identifying the key potential of DTs and BIM for managing cities of the future [55]. DL model for as-built BIM has also been developed to analyze the resilience of each element within a structure in the event of an earthquake, to enable better handling of disastrous situations [56].

4.3 Computer Vision (CV)

CV is a field in AI which utilizes visual data and processes it into purposeful information. There are only a handful of articles integrating CV with BIM, indicating that not much research has been done in this field. DT-based smart public lighting system has been proposed using CV and BIM that is capable of full-depth analysis of lighting requirements using surveillance data, resulting in considerable energy optimization and highly precise detection of pedestrians [57]. Research on BIM-CV integration has also focussed on safety management for which a concept has been developed for an automated first aid rescue system for senior citizens capable of precise fall detection, sending an emergency message and producing the most optimal rescue route accessible by equipment used for medical emergency, aided by BIM-CV integration, ultimately assisting in mitigation of life-threatening injuries to the elderly [58]. There is also a study that worked on realizing the goals for workplace safety by utilizing the semantically rich 3D data from BIM and the live field status and information through CV as an integrated system for continuous monitoring that can be beneficial to maintain safe working conditions [59].

4.4 Expert Systems

There are only a handful of research articles on the use of expert systems with BIM, a system which mimics the behaviour and judgemental capabilities of a human expert using AI. An expert system for processing visual data of existing structures into a BIM model along with an IFC-compliant information model, using advanced image processing techniques that can directly convert digital images to 3D models [60]. Case-based and rule-based reasoning expert systems have been used for automated modelling of bridge structures in BIM for rapid parametric construction modelling with great accuracy and flexibility [61].

4.5 Natural Language Processing (NLP)

The role of NLP in giving rise to conversational intelligence has been crucial, giving AI the ability to replicate and understand human speech. In the field of BIM, research has been done on developing an AI voice assistant using Amazon's Alexa technology, enabling voice-based user interaction with the BIM application to create and retrieve information, especially useful for persons with disabilities [62]. Research has been done on developing a smart question and answer system using NLP to automate information search for BIM, that is also a rich source of information exclusively on BIM [63]. This can be beneficial as a quick helpful guide for designers. After a project's closure phase, data is stored for future reference, but this can be lost due to faulty procedures of data storage. To address this issue, a study utilizes BIM for project lifecycle knowledge storage with case-based reasoning and NLP techniques for efficient processing and capturing text information and other essential project data [64]. To deal with the difficulties in object retrieval from database in BIM, an NLP-based system has been proposed to enhance user queries for object retrieval, which traditionally is time-consuming and less accurate [65]. Another research on enhancing information retrieval in BIM was done using an NLP interface system, along with an IFC concept ontology having multiple constraints, to convert search queries into executable codes to retrieve information [66]. In another study, automated classification of BIM case studies in civil engineering projects according to their purpose is carried out using NLP and unsupervised learning that can identify the model parameters for categorization [67]. Manually, this would take hours for identification and subsequent classification.

4.6 Robotics

This branch of AI has largely contributed to automation of physical tasks with great precision and stability compared to human hands, one of the reasons why it is quite popular in the field of surgery in medicine. BIM and robotics have been integrated in several applied research studies. Efficient functioning of construction robots requires explicit input information and BIM is the most reliable source of information for the robotic automation process. With its proven track record of efficiency in assembly line manufacturing, a study utilized robotics for assembling wooden frames for construction purpose, resulting in significantly faster and error-free work compared to manual labour [68]. Research has also been carried out to develop an automated brick assembling robot system with the help of a BIM-based 3D task level planning framework and coordinates extracted from the IFC model for accurately placing the bricks, which is proven to be faster than providing manual instructions to the robot [69].

One of the key challenges for robotic construction process is to tackle with complicated indoor scenarios that requires robust path coverage planning, addressed in a study focussed on enhancing coverage path for the robots through semantic mapping with BIM and using optimization techniques to enable the robotic systems to work with minimal interruption and optimum coverage distance [70]. The importance of BIM in planning workflow and movement of autonomous construction robots has been further highlighted through development of a prototype indoor painting robot system, which can convert an IFC file into a compatible format to provide information to the system, for planning tasks and the required motion and navigation [71]. Systems have also been developed to enable robots to extract BIM lifecycle information from models directly to automate planning and execution, rather than coding manually, which can be tedious for the entire lifecycle of a complex building structure [72]. Robots have also been used in the field of FM, as inspection by humans can be time-consuming, laborious as well as prone to errors and misjudgement. BIM data fed into the robots helps them to navigate the complex built environment, to inspect the facility and to provide details on issues that may exist, leading to a fully automated, hassle-free approach to FM [73]. The COVID-19 pandemic had brought construction to a halt across the globe, due to social distancing norms, lockdowns and mass migration. A prototype was designed to automate the construction of an emergency field hospital using lightweight pre-fabricated components based on BIM for planning the sequence of activities and the required motion and navigation for the robots [74]. This can be especially beneficial for humanitarian relief in situations like wars and natural disasters. Integrating BIM and robotic systems for prefabrication is another field of study which unites the manufacturing approach in off-site construction and the on-site assembly in a systematic manner. High level of precision is required for robots to identify the prefabricated components for assembling. Studies on using BIM for object recognition instead of scanning system has shown promising results in terms of being efficient in managing off-site construction activities [75]. One of the barriers to implementing fully fledged robotic systems in construction arises due to technical interoperability issues. To address this concern, a research study has used computational design technology for BIM to power construction robots at a prefabrication site and developed a 'Design-to-Manufacturing' concept for offsite construction that boosts the potential for total autonomous construction [76].

4.7 Other novel concepts

4.7.1 H-BIM (Historic building information modelling)

Studies on the use of AI technologies for H-BIM state the importance of AI for safeguarding culturally significant and historical architectural marvels, by enhancing the decision-making process in selection of structural or finishing elements to be preserved [77], in order to create an intelligent conservation management system, which can otherwise face the trouble of erroneous judgement errors by humans during the restoration work. A research case study on this topic states the necessity of automating the modelling of historical elements having sophisticated geometry, which are irregular and non-orthogonal, by using AI techniques like ML/DL, but it remains a challenge due to the varying nature of cultural elements across different historical monuments that cannot be generalized [78]. Another study proposed a semi-automated method of classification of input model data using a DL algorithm for semantic segmentation [79]. H-BIM has a great potential for the future of developing digital interactive museums.

4.7.2 Generative AI

The advent of GPT (Generative pre-trained transformers) powered by LLMs like ChatGPT has been a turning point for AI technologies. However, there has been only limited research in this field in BIM or construction industry in general. A study proposed a framework to develop a GPT for BIM that would assist in information query to provide results and 3D visualization based on dynamic prompts, which has shown to generate accurate results [25]. Another study explored the various possibilities of GPT models in construction which can be beneficial throughout the project lifecycle, but would require additional fine tuning to overcome existing limitations [80]. Since this technology utilizes existing data and transforms it into newer, intelligent solutions, it has the potential to generate innovative structural and building designs by feeding data on past designs, building codes and other relevant construction information, which can be a gamechanger for the design industry [81].

5. DISCUSSION AND FUTURE RESEARCH

After reviewing several publications on the extent of research on integrating AI technologies in BIM, it can be noted that the field is in its preliminary stage of research studies where focus has been on minor improvements in process, yet, they are quite promising and will greatly benefit in enhancing the precision of BIM technologies. AuI is an exciting future for implementing AI in the construction industry, which is a human-centric and labour-intensive industry. The implementation of BIM in general, across the industry is not widespread, which is a characteristic of the construction field that has been slow in application of new technologies, compared to other major industries of the world that lead in innovative practices. Developments in AuI and BIM have a long way to go and the field is open for research across various domains of AI as well as that of processes in construction. The civil engineering industry continues to be plagued by schedule and cost disruptions, which has major repercussions on the global economy. Labour shortage is another global issue which the industry is facing, which needs to step up implementation of innovative technologies, which would help to encourage more research in this field. This is one of the areas where human-centric nature of AuI would be greatly beneficial to the industry, as an intelligent assistant for efficient and faster completion of work. Several challenges such as training the workforce on working with new technologies remain a roadblock, especially for small and medium-sized firms in the industry, who may not be able to allocate resources where profitability is usually under threat, due to the nature of the field that is affected by the ever-changing world we live in.

The introduction of the concept of BIM to the industry facilitated automation to a great extent in improving the efficiency of construction project management, which has assisted in developing megastructures and infrastructure across developed as well developing nations at a pace which could not have been imagined only a decade before. Its ability to assist across all stages of the project including facility management after construction makes it one of the most beneficial tools in this sector. Enhancing this technology with AI would only make it more efficient, faster, reliable and precise, to such an extent that the usage of BIM should be as easy to operate as a smartphone application. Currently, BIM requires sufficient training to operate it, but with the help of AuI, operating this technology can be possible with minimal training and basic understanding of engineering concepts, with its ability for automated code compliance, rule checking, suggestions and much more. Thus, innovation and research is key to enable widespread implementation of this technology across the entire industry.

The challenges of human-machine conflict also remain contentious in this field. AI continues to be accused and targeted for its bias in decision-making and ethical issues such as its usage in warfare and manipulation. Countries around the world are working on regulating AI, which may help to ease such issues. These technologies can also be targeted by cybercrime, which can have a huge impact on its functioning. To strike a fine balance between humans and AI has been the main goal of developing AuI, which can help to overcome the drawbacks of both, and to combine the finest abilities of humans and machines for the purpose to taking technologies to a new height and unlocking possibilities for a better future. AI technologies replicate human mind; hence the human-AI partnership is a testament for a greater tomorrow and there is high need to stop viewing this technology as an enemy, but rather as an important resource for the most advanced human civilization, which has worked on dreams beyond imagination that has made life easy across the planet and needs to continue to do so.

This concept is open for years of future research across various domains of AI, across several features of BIM in which there is a scope to improve efficiency and precision, further across the various sectors in the construction industry and its processes. Scope of research especially in integrating next-gen AI technologies which are being developed at a rapid pace every day for automation towards a smarter future needs to be explored.

6. CONCLUSION

The concept of BIM has revolutionized the field of civil engineering and AI has played a similar role in changing the dynamics in the field of computer science and information technology. Keeping in mind the drawbacks associated with humans and computers, the role of AuI to create a level playing field where both man and machine equally contribute towards working efficiently and allaying the major fear of AI taking over the world, the concept can be a game-changer across industries. It is a human-machine partnership having the potential to solve the most challenging problems using each other's strengths and to minimize their weaknesses. The role of cognitive science has been mentioned which would play a key role in identifying areas where technology can enhance human behaviour. Several industries have implemented the concept of AuI, which has assisted them in improving productivity. To understand the extent of research on implementing AI in BIM, several publications were reviewed and it helped to identify sub-concepts of AI which has been instrumental to improve and automate major as well as minor processes in BIM. AI is a vast field involving several unique and important disciplines; hence it is important to understand where each of these disciplines can be useful and can lead to ideas to integrate multiple concepts to create innovative solutions. Keyword analysis showed majority of research focus on ML and DL, and on BIM processes like Scan-to-BIM, point clouds, semantic segmentation and IFC. It could also be seen that most of the work has been done in the leading developed countries, that also lead in BIM implementation. Further, it can be seen that research has been limited and mostly on ML-based algorithms, while only little research has been done on the newer advancements in this field like GPTs, which over the past few years has taken automation to a new horizon. There is a massive scope of future work in this, as AuI also remains in its nascent stage and it is essential for the field of civil engineering to innovate and upgrade automation to solve the massive challenges the industry continues to face today, which has always been the slowest to adopt to technological changes. While technology is consistently improving our lifestyle and has made life more convenient than ever before, it is getting ever more difficult to meet infrastructural needs to cater to the growing population and stronger economies across the globe because of the slow, conservative nature of this industry in innovation.

REFERENCES

[1] H. B. Cavka, S. Staub-French, and E. A. Poirier, 'Developing owner information requirements for BIM-enabled project delivery and asset management', *Autom Constr*, vol. 83, pp. 169–183, Nov. 2017, doi: 10.1016/j.autcon.2017.08.006.

[2] Y. Celik, I. Petri, and Y. Rezgui, 'Integrating BIM and Blockchain across construction lifecycle and supply chains', *Comput Ind*, vol. 148, Jun. 2023, doi: 10.1016/j.compind.2023.103886.

[3] C. Zhang, F. Wang, Y. Zou, J. Dimyadi, B. H. W. Guo, and L. Hou, 'Automated UAV image-to-BIM registration for building façade inspection using improved generalised Hough transform', *Autom Constr*, vol. 153, Sep. 2023, doi: 10.1016/j.autcon.2023.104957.

[4] V. Getuli, P. Capone, A. Bruttini, and S. Isaac, 'BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach', *Autom Constr*, vol. 114, Jun. 2020, doi: 10.1016/j.autcon.2020.103160.

[5] I. Shine and K. Whiting, 'These are the jobs most likely to be lost – and created – because of AI '.

[6] M. S. Raza, B. A. Tayeh, Y. I. Abu Aisheh, and A. M. Maglad, 'Potential features of building information modeling (BIM) for application of project management knowledge areas in the construction industry', *Heliyon*, vol. 9, no. 9, Sep. 2023, doi: 10.1016/j.heliyon.2023.e19697.

[7] UNECE, *BUILDING Information Modelling (BIM) for road infrastructure : TEM requirements and recommendations : Trans-European North-South Motorway*. UNECE, 2021.

[8] A. Koutamanis, 'Dimensionality in BIM: Why BIM cannot have more than four dimensions?', *Automation in Construction*, vol. 114. Elsevier B.V., Jun. 01, 2020. doi: 10.1016/j.autcon.2020.103153.

[9] R. Charef, H. Alaka, and S. Emmitt, ‘Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views’, *Journal of Building Engineering*, vol. 19, pp. 242–257, Sep. 2018, doi: 10.1016/j.jobe.2018.04.028.

[10] G. Bosurgi, C. Celauro, O. Pellegrino, N. Rustica, and S. Giuseppe, ‘The BIM (Building Information Modeling)-Based Approach for Road Pavement Maintenance’, in *Proceedings of the 5th International Symposium on Asphalt Pavements & Environment (APE)*, M. Pasetto, M. N. Partl, and G. Tebaldi, Eds., Cham: Springer International Publishing, 2020, pp. 480–490.

[11] J. C. P. Cheng, Q. Lu, and Y. Deng, ‘Analytical review and evaluation of civil information modeling’, *Automation in Construction*, vol. 67. Elsevier B.V., pp. 31–47, Jul. 01, 2016. doi: 10.1016/j.autcon.2016.02.006.

[12] J. Kim, T. Davis, and L. Hong, ‘Augmented Intelligence: Enhancing Human Decision Making’, in *Bridging Human Intelligence and Artificial Intelligence*, M. V Albert, L. Lin, M. J. Spector, and L. S. Dunn, Eds., Cham: Springer International Publishing, 2022, pp. 151–170. doi: 10.1007/978-3-030-84729-6_10.

[13] S. Thamm *et al.*, ‘Concept for an augmented intelligence-based quality assurance of assembly tasks in global value networks’, in *Procedia CIRP*, Elsevier B.V., 2020, pp. 423–428. doi: 10.1016/j.procir.2020.05.262.

[14] H. Nabizadeh Rafsanjani and A. H. Nabizadeh, ‘Towards human-centered artificial intelligence (AI) in architecture, engineering, and construction (AEC) industry’, *Computers in Human Behavior Reports*, vol. 11. Elsevier B.V., Aug. 01, 2023. doi: 10.1016/j.chbr.2023.100319.

[15] M. N. O. Sadiku and S. M. Musa, ‘Augmented Intelligence’, in *A Primer on Multiple Intelligences*, M. N. O. Sadiku and S. M. Musa, Eds., Cham: Springer International Publishing, 2021, pp. 191–199. doi: 10.1007/978-3-030-77584-1_15.

[16] Z. Yang *et al.*, ‘Exploiting augmented intelligence in the modeling of safety-critical autonomous systems’, *Formal Aspects of Computing*, vol. 33, no. 3, pp. 343–384, 2021, doi: 10.1007/s00165-021-00543-6.

[17] S. Boschert *et al.*, ‘Symbiotic Autonomous Systems’, 2019.

[18] M. Naveed Uddin, ‘Cognitive science and artificial intelligence: simulating the human mind and its complexity’, *Cognitive Computation and Systems*, vol. 1, no. 4, pp. 113–116, Dec. 2019, doi: https://doi.org/10.1049/ccs.2019.0022.

[19] P. Thagard, ‘Cognitive Science’, *The Stanford Encyclopedia of Philosophy (Spring 2023 Edition)*. Metaphysics Research Lab, Stanford University, 2023. Accessed: Nov. 21, 2023. [Online]. Available: https://plato.stanford.edu/archives/spr2023/entries/cognitive-science/

[20] M. Dubova, M. Galesic, and R. L. Goldstone, ‘Cognitive Science of Augmented Intelligence’, *Cogn Sci*, vol. 46, no. 12, p. e13229, Dec. 2022, doi: https://doi.org/10.1111/cogs.13229.

[21] N. Kriegeskorte and P. K. Douglas, ‘Cognitive computational neuroscience’, *Nature Neuroscience*, vol. 21, no. 9. Nature Publishing Group, pp. 1148–1160, Sep. 01, 2018. doi: 10.1038/s41593-018-0210-5.

[22] M. Paranthaman and S. Palanivel Rajan, ‘Augmented Intelligence: Deep Learning Models for Healthcare’, in *Augmented Intelligence in Healthcare: A Pragmatic and Integrated Analysis*, S. Mishra, H. K. Tripathy, P. Mallick, and K. Shaalan, Eds., Singapore: Springer Nature Singapore, 2022, pp. 167–187. doi: 10.1007/978-981-19-1076-0_10.

[23] A. Lui and G. W. Lamb, ‘Artificial intelligence and augmented intelligence collaboration: regaining trust and confidence in the financial sector’, *Information & Communications Technology Law*, vol. 27, no. 3, pp. 267–283, Sep. 2018, doi: 10.1080/13600834.2018.1488659.

[24] F. Zhang, A. P. C. Chan, A. Darko, Z. Chen, and D. Li, ‘Integrated applications of building information modeling and artificial intelligence techniques in the AEC/FM industry’, *Automation in Construction*, vol. 139. Elsevier B.V., Jul. 01, 2022. doi: 10.1016/j.autcon.2022.104289.

[25] J. Zheng and M. Fischer, ‘Dynamic prompt-based virtual assistant framework for BIM information search’, *Autom Constr*, vol. 155, Nov. 2023, doi: 10.1016/j.autcon.2023.105067.

[26] N. J. van Eck and L. Waltman, ‘CitNetExplorer: A new software tool for analyzing and visualizing citation networks’, *J Informetr*, vol. 8, no. 4, pp. 802–823, 2014, doi: https://doi.org/10.1016/j.joi.2014.07.006.

[27] H. M. Reza, M. Mojtaba, A. Ali, M. Igor, and A. Mehrdad, ‘Analysis of Citation Networks in Building Information Modeling Research’, *J Constr Eng Manag*, vol. 144, no. 8, p. 04018064, Aug. 2018, doi: 10.1061/(ASCE)CO.1943-7862.0001492.

[28] Y. Shen and Y. Pan, ‘BIM-supported automatic energy performance analysis for green building design using explainable machine learning and multi-objective optimization’, *Appl Energy*, vol. 333, Mar. 2023, doi: 10.1016/j.apenergy.2022.120575.

[29] H. H. Hosamo, M. S. Tingstveit, H. K. Nielsen, P. R. Svennevig, and K. Svidt, ‘Multiobjective optimization of building energy consumption and thermal comfort based on integrated BIM framework with machine learning-NSGA II’, *Energy Build*, vol. 277, Dec. 2022, doi: 10.1016/j.enbuild.2022.112479.

[30] K. Kanna, K. AIT Lachguer, and R. Yaagoubi, ‘MyComfort: An integration of BIM-IoT-machine learning for optimizing indoor thermal comfort based on user experience’, *Energy Build*, vol. 277, Dec. 2022, doi: 10.1016/j.enbuild.2022.112547.

[31] D. Wang and F. Chang, ‘Application of machine learning-based BIM in green public building design’, *Soft comput*, vol. 27, no. 13, pp. 9031–9040, Jul. 2023, doi: 10.1007/s00500-023-08162-4.

[32] J. C. P. Cheng, W. Chen, K. Chen, and Q. Wang, ‘Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms’, *Autom Constr*, vol. 112, Apr. 2020, doi: 10.1016/j.autcon.2020.103087.

[33] J. J. McArthur, N. Shahbazi, R. Fok, C. Raghubar, B. Bortoluzzi, and A. An, ‘Machine learning and BIM visualization for maintenance issue classification and enhanced data collection’, *Advanced Engineering Informatics*, vol. 38, pp. 101–112, Oct. 2018, doi: 10.1016/j.aei.2018.06.007.

[34] T. Bloch and R. Sacks, ‘Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models’, *Autom Constr*, vol. 91, pp. 256–272, Jul. 2018, doi: 10.1016/j.autcon.2018.03.018.

[35] S. Sobhkhiz and T. El-Diraby, ‘Dynamic integration of unstructured data with BIM using a no-model approach based on machine learning and concept networks’, *Autom Constr*, vol. 150, Jun. 2023, doi: 10.1016/j.autcon.2023.104859.

[36] M. Ryu, H. L. Truong, and M. Kannala, 'Understanding quality of analytics trade-offs in an end-to-end machine learning-based classification system for building information modeling', *J Big Data*, vol. 8, no. 1, Dec. 2021, doi: 10.1186/s40537-021-00417-x.

[37] T. Su, H. Li, and Y. An, 'A BIM and machine learning integration framework for automated property valuation', *Journal of Building Engineering*, vol. 44, Dec. 2021, doi: 10.1016/j.jobe.2021.102636.

[38] B. Koo, R. Jung, and Y. Yu, 'Automatic classification of wall and door BIM element subtypes using 3D geometric deep neural networks', *Advanced Engineering Informatics*, vol. 47, Jan. 2021, doi: 10.1016/j.aei.2020.101200.

[39] C. Emunds, N. Pauen, V. Richter, J. Frisch, and C. van Treeck, 'SpaRSE-BIM: Classification of IFC-based geometry via sparse convolutional neural networks', *Advanced Engineering Informatics*, vol. 53, Aug. 2022, doi: 10.1016/j.aei.2022.101641.

[40] H. Abdirad and P. Mathur, 'Artificial intelligence for BIM content management and delivery: Case study of association rule mining for construction detailing', *Advanced Engineering Informatics*, vol. 50, Oct. 2021, doi: 10.1016/j.aei.2021.101414.

[41] S. Banihashemi, S. Khalili, M. Sheikhkhoshkar, and A. Fazeli, 'Machine learning-integrated 5D BIM informatics: building materials costs data classification and prototype development', *Innovative Infrastructure Solutions*, vol. 7, no. 3, Jun. 2022, doi: 10.1007/s41062-022-00822-y.

[42] F. Pour Rahimian, S. Seyedzadeh, S. Oliver, S. Rodriguez, and N. Dawood, 'On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning', *Autom Constr*, vol. 110, Feb. 2020, doi: 10.1016/j.autcon.2019.103012.

[43] W. Wei, Y. Lu, T. Zhong, P. Li, and B. Liu, 'Integrated vision-based automated progress monitoring of indoor construction using mask region-based convolutional neural networks and BIM', *Autom Constr*, vol. 140, Aug. 2022, doi: 10.1016/j.autcon.2022.104327.

[44] N. Kayhani, B. McCabe, and B. Sankaran, 'Semantic-aware quality assessment of building elements using graph neural networks', *Autom Constr*, vol. 155, Nov. 2023, doi: 10.1016/j.autcon.2023.105054.

[45] S. Ghorbany, E. Noorzai, and S. Yousefi, 'BIM-based solution to enhance the performance of public-private partnership construction projects using copula bayesian network', *Expert Syst Appl*, vol. 216, Apr. 2023, doi: 10.1016/j.eswa.2023.119501.

[46] Y. Hong, A. W. A. Hammad, A. Akbarnezhad, and M. Arashpour, 'A neural network approach to predicting the net costs associated with BIM adoption', *Autom Constr*, vol. 119, Nov. 2020, doi: 10.1016/j.autcon.2020.103306.

[47] F. Xu and Q. Liu, 'Building energy consumption optimization method based on convolutional neural network and BIM', *Alexandria Engineering Journal*, vol. 77, pp. 407–417, Aug. 2023, doi: 10.1016/j.aej.2023.06.084.

[48] R. Zhai, J. Zou, Y. He, and L. Meng, 'BIM-driven data augmentation method for semantic segmentation in superpoint-based deep learning network', *Autom Constr*, vol. 140, Aug. 2022, doi: 10.1016/j.autcon.2022.104373.

[49] S. Tang, X. Li, X. Zheng, B. Wu, W. Wang, and Y. Zhang, 'BIM generation from 3D point clouds by combining 3D deep learning and improved morphological approach', *Autom Constr*, vol. 141, Sep. 2022, doi: 10.1016/j.autcon.2022.104422.

[50] J. W. Ma, T. Czerniawski, and F. Leite, ‘Semantic segmentation of point clouds of building interiors with deep learning: Augmenting training datasets with synthetic BIM-based point clouds’, *Autom Constr*, vol. 113, May 2020, doi: 10.1016/j.autcon.2020.103144.

[51] B. Wang, Q. Wang, J. C. P. Cheng, and C. Yin, ‘Object verification based on deep learning point feature comparison for scan-to-BIM’, *Autom Constr*, vol. 142, Oct. 2022, doi: 10.1016/j.autcon.2022.104515.

[52] B. Wang, Q. Wang, J. C. P. Cheng, C. Song, and C. Yin, ‘Vision-assisted BIM reconstruction from 3D LiDAR point clouds for MEP scenes’, *Autom Constr*, vol. 133, Jan. 2022, doi: 10.1016/j.autcon.2021.103997.

[53] Y. S. Yu, S. H. Kim, W. B. Lee, and B. S. Koo, ‘Ensemble-based Deep Learning Approach for Performance Improvement of BIM Element Classification’, *KSCE Journal of Civil Engineering*, vol. 27, no. 5, pp. 1898–1915, May 2023, doi: 10.1007/s12205-023-2331-y.

[54] P. Zhou and N. El-Gohary, ‘Semantic information alignment of BIMs to computer-interpretable regulations using ontologies and deep learning’, *Advanced Engineering Informatics*, vol. 48, Apr. 2021, doi: 10.1016/j.aei.2020.101239.

[55] W. Wang, H. Guo, X. Li, S. Tang, J. Xia, and Z. Lv, ‘Deep learning for assessment of environmental satisfaction using BIM big data in energy efficient building digital twins’, *Sustainable Energy Technologies and Assessments*, vol. 50, Mar. 2022, doi: 10.1016/j.seta.2021.101897.

[56] C. Galera-Zarco and G. Floros, ‘A deep learning approach to improve built asset operations and disaster management in critical events: an integrative simulation model for quicker decision making’, *Ann Oper Res*, 2023, doi: 10.1007/s10479-023-05247-z.

[57] Y. Tan, P. Chen, W. Shou, and A. M. Sadick, ‘Digital Twin-driven approach to improving energy efficiency of indoor lighting based on computer vision and dynamic BIM’, *Energy Build*, vol. 270, Sep. 2022, doi: 10.1016/j.enbuild.2022.112271.

[58] Y. Chen, Y. Zhang, B. Xiao, and H. Li, ‘A framework for the elderly first aid system by integrating vision-based fall detection and BIM-based indoor rescue routing’, *Advanced Engineering Informatics*, vol. 54, Oct. 2022, doi: 10.1016/j.aei.2022.101766.

[59] A. S. Kulinan, M. Park, P. P. W. Aung, G. Cha, and S. Park, ‘Advancing construction site workforce safety monitoring through BIM and computer vision integration’, *Autom Constr*, vol. 158, Feb. 2024, doi: 10.1016/j.autcon.2023.105227.

[60] O. Doukari and D. Greenwood, ‘Automatic generation of building information models from digitized plans’, *Autom Constr*, vol. 113, p. 103129, 2020, doi: https://doi.org/10.1016/j.autcon.2020.103129.

[61] W. Meng, H. Zhang, Q. Ai, T. Bao, and J. Yan, ‘CBR-RBR fusion based parametric rapid construction method of bridge BIM model’, *Advanced Engineering Informatics*, vol. 57, p. 102086, 2023, doi: https://doi.org/10.1016/j.aei.2023.102086.

[62] F. Elghaish, J. K. Chauhan, S. Matarneh, F. Pour Rahimian, and M. R. Hosseini, ‘Artificial intelligence-based voice assistant for BIM data management’, *Autom Constr*, vol. 140, Aug. 2022, doi: 10.1016/j.autcon.2022.104320.

[63] T. H. Lin, Y. H. Huang, and A. Putranto, ‘Intelligent question and answer system for building information modeling and artificial intelligence of things based on the bidirectional encoder

representations from transformers model', *Autom Constr*, vol. 142, Oct. 2022, doi: 10.1016/j.autcon.2022.104483.

[64] H. Wang, X. Meng, and X. Zhu, 'Improving knowledge capture and retrieval in the BIM environment: Combining case-based reasoning and natural language processing', *Autom Constr*, vol. 139, Jul. 2022, doi: 10.1016/j.autcon.2022.104317.

[65] S. Wu, Q. Shen, Y. Deng, and J. Cheng, 'Natural-language-based intelligent retrieval engine for BIM object database', *Comput Ind*, vol. 108, pp. 73–88, Jun. 2019, doi: 10.1016/j.compind.2019.02.016.

[66] M. Yin, L. Tang, C. Webster, S. Xu, X. Li, and H. Ying, 'An ontology-aided, natural language-based approach for multi-constraint BIM model querying', *Journal of Building Engineering*, vol. 76, Oct. 2023, doi: 10.1016/j.jobe.2023.107066.

[67] N. Jung and G. Lee, 'Automated classification of building information modeling (BIM) case studies by BIM use based on natural language processing (NLP) and unsupervised learning', *Advanced Engineering Informatics*, vol. 41, Aug. 2019, doi: 10.1016/j.aei.2019.04.007.

[68] O. Wong Chong, J. Zhang, R. M. Voyles, and B. C. Min, 'BIM-based simulation of construction robotics in the assembly process of wood frames', *Autom Constr*, vol. 137, May 2022, doi: 10.1016/j.autcon.2022.104194.

[69] L. Ding, W. Jiang, Y. Zhou, C. Zhou, and S. Liu, 'BIM-based task-level planning for robotic brick assembly through image-based 3D modeling', *Advanced Engineering Informatics*, vol. 43, Jan. 2020, doi: 10.1016/j.aei.2019.100993.

[70] Z. Chen *et al.*, 'Improved coverage path planning for indoor robots based on BIM and robotic configurations', *Autom Constr*, vol. 158, p. 105160, Feb. 2024, doi: 10.1016/j.autcon.2023.105160.

[71] S. Kim, M. Peavy, P. C. Huang, and K. Kim, 'Development of BIM-integrated construction robot task planning and simulation system', *Autom Constr*, vol. 127, Jul. 2021, doi: 10.1016/j.autcon.2021.103720.

[72] K. Kim and M. Peavy, 'BIM-based semantic building world modeling for robot task planning and execution in built environments', *Autom Constr*, vol. 138, Jun. 2022, doi: 10.1016/j.autcon.2022.104247.

[73] J. Chen, W. Lu, Y. Fu, and Z. Dong, 'Automated facility inspection using robotics and BIM: A knowledge-driven approach', *Advanced Engineering Informatics*, vol. 55, Jan. 2023, doi: 10.1016/j.aei.2022.101838.

[74] Y. Gao, J. Meng, J. Shu, and Y. Liu, 'BIM-based task and motion planning prototype for robotic assembly of COVID-19 hospitalisation light weight structures', *Autom Constr*, vol. 140, Aug. 2022, doi: 10.1016/j.autcon.2022.104370.

[75] M. Dawod and S. Hanna, 'BIM-assisted object recognition for the on-site autonomous robotic assembly of discrete structures', *Construction Robotics*, vol. 3, no. 1–4, pp. 69–81, Dec. 2019, doi: 10.1007/s41693-019-00021-9.

[76] W. Anane, I. Iordanova, and C. Ouellet-Plamondon, 'BIM-driven computational design for robotic manufacturing in off-site construction: an integrated Design-to-Manufacturing (DtM) approach', *Autom Constr*, vol. 150, Jun. 2023, doi: 10.1016/j.autcon.2023.104782.

[77] D. Bienvenido-Huertas, J. E. Nieto-Julián, J. J. Moyano, J. M. Macías-Bernal, and J. Castro, ‘Implementing Artificial Intelligence in H-BIM Using the J48 Algorithm to Manage Historic Buildings’, *International Journal of Architectural Heritage*, vol. 14, no. 8, pp. 1148–1160, Sep. 2020, doi: 10.1080/15583058.2019.1589602.

[78] V. A. Cotella, ‘From 3D point clouds to HBIM: Application of Artificial Intelligence in Cultural Heritage’, *Automation in Construction*, vol. 152. Elsevier B.V., Aug. 01, 2023. doi: 10.1016/j.autcon.2023.104936.

[79] V. Croce, ‘Digital Heritage Classification via Machine Learning and H-BIM’, *Nexus Netw J*, vol. 25, pp. 415–421, Jun. 2023, doi: 10.1007/s00004-023-00725-0.

[80] A. Saka *et al.*, ‘GPT models in construction industry: Opportunities, limitations, and a use case validation’, *Developments in the Built Environment*, vol. 17, p. 100300, 2024, doi: https://doi.org/10.1016/j.dibe.2023.100300.

[81] W. Liao, X. Lu, Y. Fei, Y. Gu, and Y. Huang, ‘Generative AI design for building structures’, *Autom Constr*, vol. 157, p. 105187, 2024, doi: https://doi.org/10.1016/j.autcon.2023.105187.

[82] AIA, ‘G202-2013 Building Information Modelling Protocol Form’, *American Institute of Architects*, 2013.