Applications of Machine Learning, Computer Vision, and Robotics in the Construction Engineering and Management Domain

Muhammad Umer[1] and Eric M. Wetzel, Ph.D.[1]

[1] Auburn University, Auburn, AL
mzu0009@auburn.edu

Abstract
The recent progress in AI has brought an unprecedented transformation in our lives. It is hardly any area of human life that is not impacted by this paradigm-changing technology. Infamous as a slow technology adopter, the construction industry has also started to embrace this technology keeping in view of its movement towards Construction 4.0. This manuscript is a preliminary attempt to assess the AI and associated technologies' applications in the construction engineering and management (CEM) domain. Through secondary data published, an attempt has been made to elaborate on Machine Learning, Computer Vision, and Robotics applications in CEM domain, trend of applications and map the respective CEM activities and technologies together. The findings reveal extensive and diversified applications of Machine Learning, Computer Vision, and Robotics. Furthermore, the use of various technologies in CEM domain reflects a growing inclination towards combining digital and automated solutions. There is a strong preference for machine learning (ML) and computer vision (CV) in tasks that involve analysis and visual processing. Robotics is selectively and strategically employed for physical task execution and risk reduction. Convolutional Neural Networks (CNN) dominate the landscape of CEM domain, being the most frequently referenced algorithm in the dataset. Their popularity highlights their efficiency in image processing and sophisticated pattern recognition tasks, which are critical in a variety of construction applications. In this paper, the algorithm-to-CEM application mapping demonstrates a detailed grasp of each AI technique's strengths and use cases in the field of construction management.

Keywords
Artificial Intelligence, Computer Vision, Robotics, Automation, Construction Engineering and Management

1. Introduction

The advancement of artificial intelligence technology is currently opening new potential in the building industry. Machine learning is a hot topic in the field of artificial intelligence, and it plays a critical part in the process of making construction "smart." (Xu et al., 2021). Machine Learning focuses on the development and utilization of computer systems that can acquire knowledge and make predictions based on past data or experiences, utilizing statistical methods, without the need for explicit programming (Abioye et al., (2021). Machine learning algorithms can be classified in numerous ways. ML models can be categorized based on the level of supervision they receive during the training phase. The ML models can be classified as supervised learning, unsupervised learning, reinforcement learning (Baduge et al., 2022), and Deep Learning (LeCun et al., 2015; Oyedele et al., 2021; Schmidhuber, 2015; Abioye et al., 2021). Computer vision (CV) is a technology that allows computers to analyze digital images or videos and extract valuable information (Davies, 2022; Wiley & Lucas, 2018). It enables the detection, identification, and automation of processes by integrating inputs from the physical world (Wiley & Lucas, 2018). It is a fusion of various principles, such as digital image processing, machine learning, and pattern recognition (Abioye et al., 2021). Construction is a labor-intensive sector of the economy with a challenging workplace. Commercial bricklaying robots, building and delivery drones, robotics for monitoring and inspection, and automated bulldozers are only a few examples of the expanding use of automation in the built environment in order to address dangerous, repetitive, and labor shortage issues (Oesterreich & Teuteberg, 2016). Cai et al. (2019) carried out an in-depth market analysis of the technologies and developers of automation technologies and robots. 90 commercial businesses were found, of which 24 manufactured products for the construction of high-rise buildings, including 17 for automated construction systems, 6 for automated logistics systems, 4 for façade cleaning, 5 for façade inspection, and 6 for façade installation (some companies provided more than one type of products). After removing duplicates, they obtained 105 companies providing products on construction automation and robotics (not limited to high-rise building construction) in total. According to their major businesses, these companies were divided into five categories, while the companies identified for high-rise building construction mainly fall into the categories of "Construction machinery company" (3 companies, 11.1%), "Construction company" (12 companies, 44.4%) and "Construction automation and robotics company" (12 companies, 44.4%).

This paper reports the findings of an archive investigation, the respective publications and their secondary citations were examined to assess how they reported on the use of Machine Learning, Computer Vision, and Robotics in the field of construction engineering and management. The authors note that there is an immense crossover between these three technologies because robots utilize computer vision which is essentially powered by ML algorithms.

2. Methods and Materials

This paper is an archival study of Abioye et al. 2021; Ivanova et al. 2023; Garcia et al. 2022; Akinosho et al. 2020. These papers and their secondary citations were analyzed for their reporting of Machine Learning, Computer Vision, and Robotics applications in construction engineering and management domain. Fig. 1. presents the methodology.

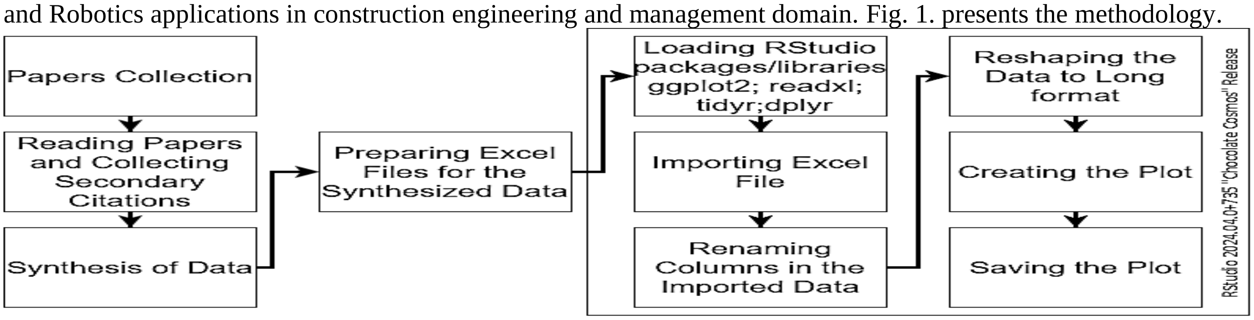


Fig. 1. Paper methodology

- Data collection: Google Scholar, Web of Science, Scopus were used to collect above mentioned papers that extensively reported AI, Computer Vision, and Robotics applications in construction engineering and management domains.
- Review: The collected papers were reviewed to extract pertinent information and all secondary citations that were present in the original papers.
- Synthesis of information: The information collected was then synthesized from the point of view of commonality and information ad-on.
- Preparing data for analysis: The synthesized data was then transformed into MS Excel files for further analysis and visualizations.
- Loading RStudio packages/libraries: Relevant libraries for RStudio were loaded/installed. The particular libraries used for data analysis and visualization were readxl; tidyr; dplyr; ggplot2. The R library tidyr is specifically designed to assist users in organizing their data, a critical process in data analysis. Data tidying is converting data into a format that facilitates easy and intuitive examination. The ggplot2 package in R is a robust and extensively utilized framework for generating visually pleasing data visualizations. The concept is derived from the "Grammar of Graphics," which offers a systematic approach to constructing graphical representations of data. readxl was used to read Excel files into the RStudio environment. The dplyr package in RStudio is a fundamental tool for manipulating data inside the tidyverse, which is a set of R packages specifically created for data science.
- Importing Excel files: The synthesized data was then imported into RStudio using readxl.
- Renaming columns names: Columns in the imported data were renamed for ease of data handling.
- Reshaping the data to long format: Using the tidyr and dplr package, the imported data was transformed into long format to facilitate analysis. The aim for reshaping the data was to ensure that each row corresponds to one respective data point/value.
- Plotting the data: Using ggplot2, the pertinent data was plotted (refer Fig. 2. to Fig. 5. below).

- Saving the plot: The final step was to export the generated plot in *.png format.

3. Results and Discussion

3. 1 Machine Learning, Computer Vision, and Robotics Applications in CEM Domain

Fig.2. presents a summary of automation and AI applications in Construction Engineering and Management (CEM) domain. The data has been sourced from (Abioye et al., 2021). Fig. 2. illustrates the utilization of three domains of Artificial Intelligence—Machine Learning (ML), Computer Vision (CV), and Robotics—into different areas of construction engineering and management, including Health and Safety, Scheduling, Cost Estimation, and more. An evident pattern arises from the data as presented in Fig.2. below.

Machine Learning is widely used in all fields (ML found utilized- 88% versus ML(N/A) not found utilized-12%), highlighting its adaptable role in improving and automating several processes in the CM domain. Significant uses of Machine Learning (ML) are Health and Safety, Scheduling, Cost Estimation, Contracts and Conflict Mgt, Supply Chain and Logistics, Site Monitoring & Performance Evaluation, Material Mgt, Offsite Assembly, Plant and Equipment Mgt, Project Planning, Knowledge Mgt, Design, Risk Mgt, Temporary Structures, Bids/Tenders.

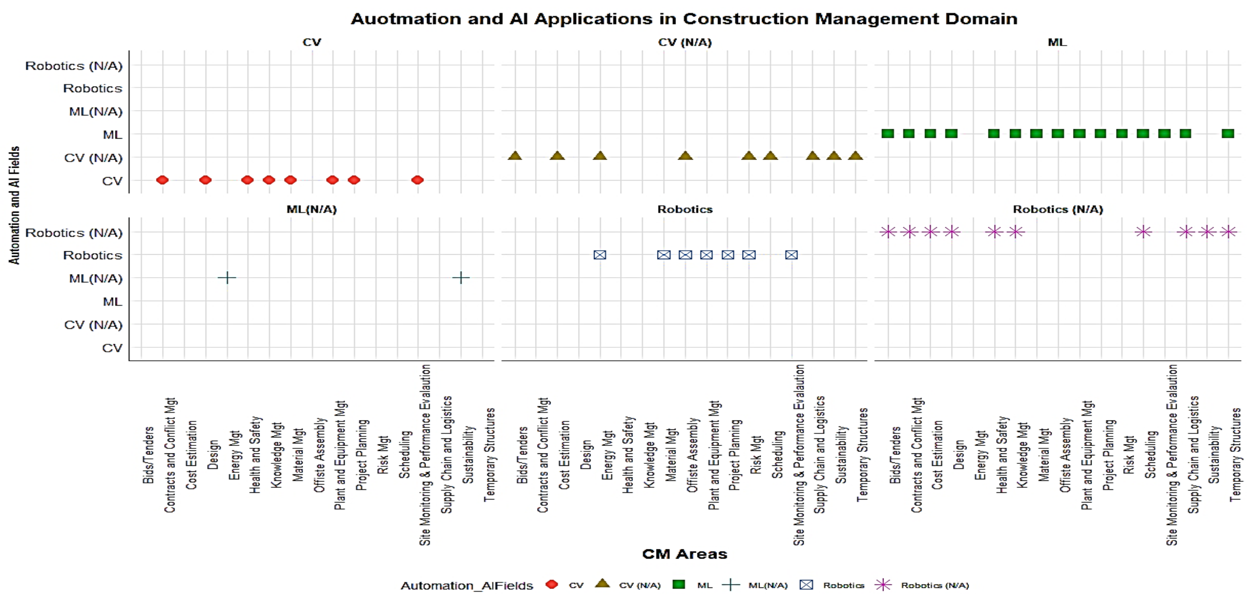


Fig. 2. Automation and AI Applications in CEM Domain (Data from Abioye et al. 2021)

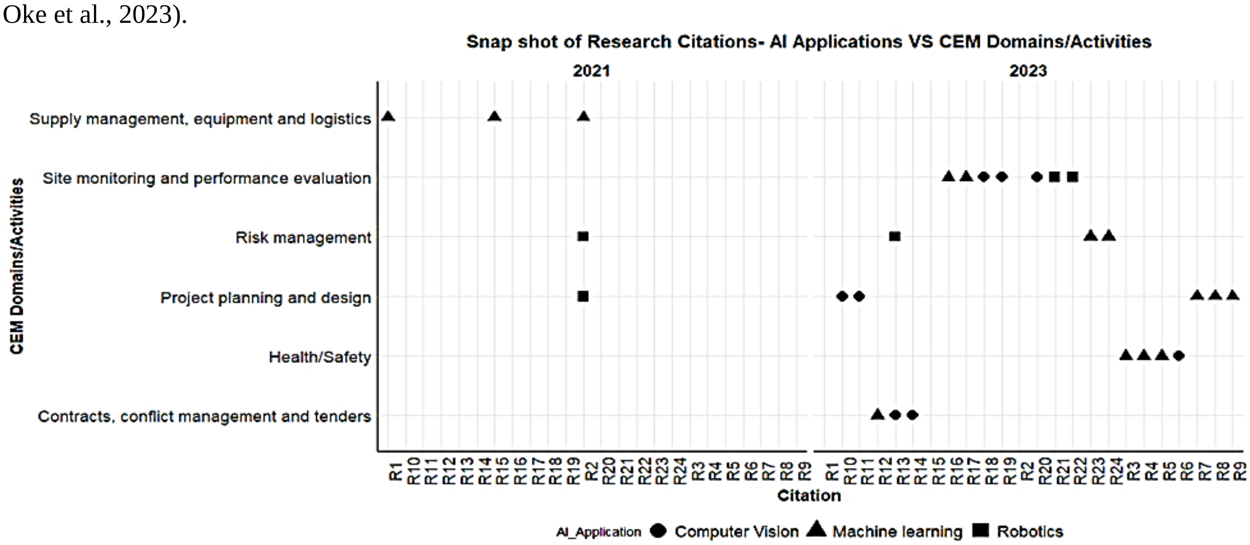
Computer Vision is used selectively (CV found utilized- 47% versus CV(N/A) not found utilized-53%), primarily in domains where image processing is essential. Significant uses of Computer Vision are Health and Safety, Scheduling, Cost Estimation, Contracts and Conflict Mgt, Supply Chain and Logistics, Site Monitoring & Performance Evaluation, Material Mgt, Offsite Assembly, Plant and Equipment Mgt, Project Planning, Knowledge Mgt, Design. The application of robotics is limited (Robotics found utilized-41% versus Robotics(N/A) not found utilized-59%) and hence establishes necessity for automation in specific domains of construction management. With its limited application, Robotics are utilized in various areas such as Site Monitoring & Performance Evaluation, Material Management (Mgt), Offsite Assembly, Plant and Equipment Mgt, Project Planning, Knowledge Mgt, Design, Risk Mgt, Temporary Structures, Bids/Tenders, Energy Mgt.

Having the evidence that indeed automation and AI techniques have multitude of applications in the CEM domain, an attempt was made to map recent citations for the three categories against the CEM domains/activities. Fig 3 presents the insight visually.

3.2 Trend of Machine Learning, Computer Vision, and Robotics Application in the Construction Industry

The presented data (Fig. 3.) presents an analysis of the application of Machine Learning (ML), Computer Vision (CV), and Robotics in different domains and activities in Construction Engineering Management (CEM). As per the work by Ivanova et al. (2023), ML and CV are widely utilized in several CEM domains/activities, with Robotics being comparatively less common.

Within the domain of Contracts, Conflict Management, and Tenders, there is a significant preference for CV (67%), suggesting a dependence on visual data analysis, potentially for the purpose of contract paperwork and tender assessments (Ivanova et al., 2023; Zhang et al., 2023; Ottoni et al., 2023; Alsugair et al., 2023). The field of Health and Safety is primarily influenced by Machine Learning (ML) technology, accounting for 60% of its concentration. This indicates an emphasis on using predictive analytics to prevent accidents and monitor health conditions (Ivanova et al., 2023; Alkaissy et al., 2023; Anwer et al., 2023; Luo et al., 2023; Chern et al., 2023; Chen et al., 2023). Project Planning and Design involves a more equitable allocation of usage, with Machine Learning (50%) and Computer Vision (33%) playing significant roles, perhaps in automating design processes and creating visual project simulations. Robotics also makes a lesser but noteworthy contribution (17%) (Ivanova et al., 2023; Abioye et al., 2021; Ramadan & Elgendi, 2023; Y. Wang et al., 2023; Sánchez-Garrido et al., 2023; X. Wu et al., 2023; S. Wang et al., 2023). The application in the domain of Risk Management is equally divided between Machine Learning (ML) and Robotics, with each accounting for 50% (Ivanova et al., 2023; Abioye et al., 2021; Ottoni et al., 2023; Wen et al., 2023; Lin et al., 2023). The field of Supply Management, Equipment, and Logistics relies entirely on Machine Learning (100%), indicating a significant dependence on data-driven methods for planning logistics and managing inventory (Ivanova et al., 2023; Pan & Zhang, 2021; Abioye et al., 2021; Xu et al 2021). Site Monitoring and Performance Evaluation incorporates a combination of all three technologies, with a somewhat greater emphasis on CV (43%). This suggests that image and video analytics are likely being utilized for site supervision (Ivanova et al., 2023; Sadatnya et al., 2023; Geng et al., 2023; Ahila Priyadharshini et al., 2023; Alsakka et al., 2023; Zou et al., 2023; Abu Kharmeh et al., 2023; Oke et al., 2023).



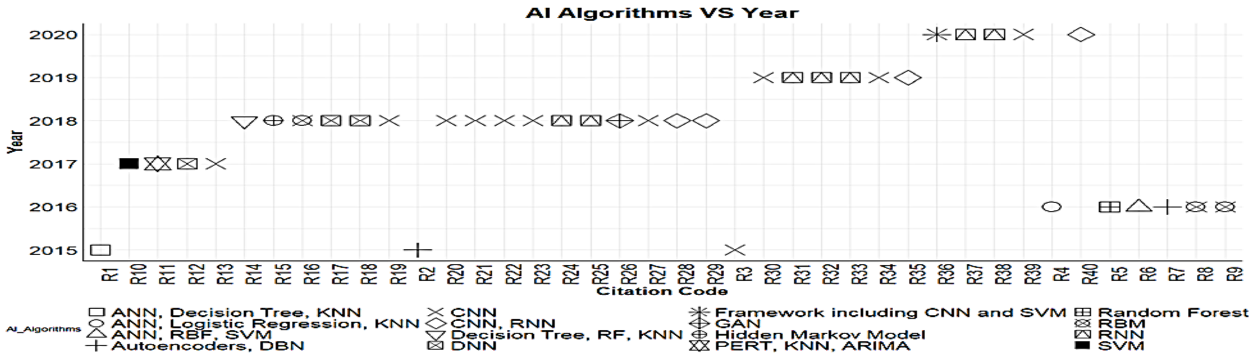
Citation Legend						
R1=Pan & Zhang,(2021)	R2=Abioye et al.,(2021)	R2=Abioye et al.,(2021)	R2=Abioye et al.,(2021)	R3=Alkaissy et al.,(2023)	R4=Anwer et al.,(2023)	R5=Luo et al.,(2023)
R6=Chern et al.,(2023)	R6=Chen et al.,(2023)	R7=Ramadan & Elgendi,(2023)	R8=Y. Wang et al.,(2023)	R9=Sánchez-Garrido et al.,(2023)	R10=X. Wu et al.,(2023)	R11=S. Wang et al.,(2023)
R12=Zhang et al.,(2023)	R13=Ottoni et al.,(2023)	R13=Ottoni et al.,(2023)	R14=Alsugair et al.,(2023)	R15=Xu et al.,(2021)	R16=Sadatnya et al.,(2023)	R17=Geng et al.,(2023)
R18=Ahila Priyadharshini et al., (2023)	R19=Alsakka et al.,(2023)	R20=Zou et al.,(2023)	R21=Abu Kharmeh et al.,(2023)	R22=Oke et al.,(2023)	R23=Wen et al.,(2023)	R24=Lin et al.,(2023)

Fig. 3. Trend of AI Application in the Construction Industry (Data from Ivanova et al. 2023)

In conclusion, the use of various technologies in CEM reflects a growing inclination towards combining digital and automated solutions. There is a strong preference for machine learning (ML) and computer vision (CV) in tasks that involve analysis and visual processing. Robotics is selectively and strategically employed for physical task execution and risk reduction. An attempt was made to peel off one more layer of data to understand the types of AI algorithms and their utilization in the context of construction engineering and management (CEM). Fig 4. presents the AI algorithms versus year and Fig.5. presents the CEM Activities in the Context of AI Utilization VS Year pattern.

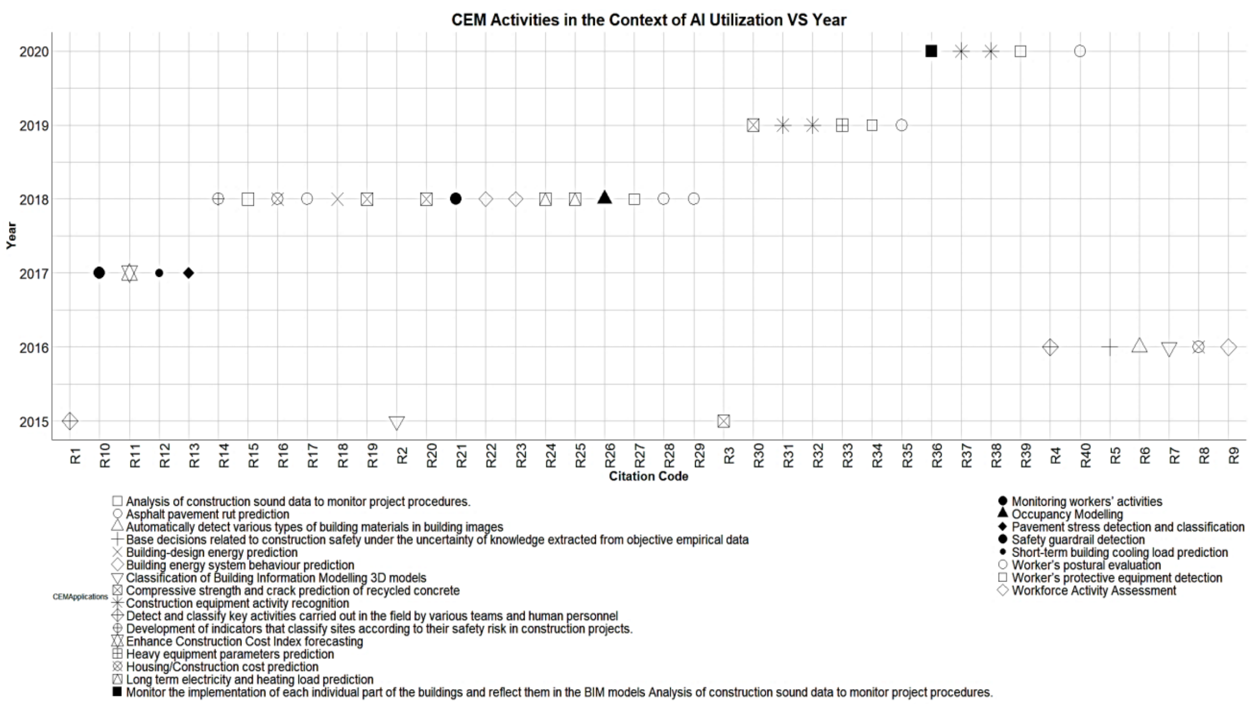
Fig. 4. and Fig. 5. are interpreted in terms of frequency of AI algorithms, year wise AI algorithms used in CEM applications. From the point of view of frequency of AI/ML Algorithms, Convolutional Neural Networks (CNN) dominate the landscape of Construction Engineering and Management (CEM), being the most frequently referenced algorithm in the dataset. Their popularity highlights their efficiency in image processing and sophisticated pattern

recognition tasks, which are critical in a variety of construction applications. Following CNN, Recurrent Neural Networks (RNN) are the second most cited, demonstrating its ability to handle sequential data. Other algorithms, such as K-Nearest Neighbors (KNN) and Artificial Neural Networks (ANN), are used as well, demonstrating a varied spectrum of AI applications in CEM. When attention is drawn to yearly trends.



Legend Citation									
R1=Akhavian & Behzadan, (2015)	R2=Wang et al., (2015)	R3=Koch et al., (2015)	R4=Akhavian & Behzadan, (2016)	R5=Tixier et al.,(2016)	R6=Rashidi et al., (2016)	R7=Wang et al., (2016)	R8=Rafiei & Adeli, (2016)	R9=Mocanu et al., (2016)	R10=Nath et al., (2017)
R11=Wang & Ashuri, (2017)	R12=Fan et al., (2017)	R13=Khaitan et al., (2017)	R14=Poh et al., (2018)	R15=Zhang, Lee, Scarpiniti, & Uncini, (2018)	R16=Rafiei & Adeli, (2018)	R17=Gong et al., (2018)	R18=Singaravel et al., (2018)	R19=Deng et al., (2018)	R20=Dorafshan et al., (2018)
R21=Kolar et al., (2018)	R22=H. Luo et al., (2018)	R23=X. Luo et al., (2018)	R24=Rahman et al., (2018)	R25=Rahman & Smith, (2018)	R26=Chen & Jiang, (2018)	R27=Fang et al., (2018)	R28=Zhang, Yan, & Li, (2018)	R29=Gard et al., (2018)	R30=Beckman et al., (2019)
R31=Rashid & Louis, (2019)	R32=Hernandez et al., (2019)	R33=Gao et al., (2019)	R34=Wu et al., (2019)	R35=Yu et al., (2019)	R36=Pour et al., (2020)	R37=Slaton et al., (2020)	R38=Sherafat et al., (2020)	R39=Nath et al., (2020)	R40=Yang et al., (2020)

Fig. 4. AI Algorithms VS Year (Data from Garcia et al. 2022; Akinosho et al. 2020)



Legend Citation									
R1=Akhavian & Behzadan, (2015)	R2=Wang et al., (2015)	R3=Koch et al., (2015)	R4=Akhavian & Behzadan, (2016)	R5=Tixier et al.,(2016)	R6=Rashidi et al., (2016)	R7=Wang et al., (2016)	R8=Rafiei & Adeli, (2016)	R9=Mocanu et al., (2016)	R10=Nath et al., (2017)
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R31=Rashid & Louis, (2019)	R32=Hernandez et al., (2019)	R33=Gao et al., (2019)	R34=Wu et al., (2019)	R35=Yu et al., (2019)	R36=Pour et al., (2020)	R37=Slaton et al., (2020)	R38=Sherafat et al., (2020)	R39=Nath et al., (2020)	R40=Yang et al., (2020)

Fig. 5. CEM Activities in the Context of AI Utilization VS Year (Data from Garcia et al. 2022; Akinosho et al. 2020)

The analysis reveals a developing landscape of AI algorithm utilization in CEM. In the previous years (2015-2016), there was a broad use of algorithms such as artificial neural network (ANN), Decision Trees, and k-nearest neighbors (KNN), indicating an exploration phase in AI adoption. In recent years (2019-2020), there has been a considerable shift toward advanced algorithms such as convolutional neural networks (CNN) and recurrent neural networks (RNN). This trend represents a maturing in the industry's approach to AI, as it progresses from foundational algorithms to more sophisticated ones capable of handling complex data and providing deeper insights. This evolution reflects the overall advancement in AI capabilities to handle more complex activities, which necessitates increasingly powerful analytical tools. The assessment of AI/ML algorithms used in CEM applications establishes a link between certain AI/ML algorithms and CEM applications. It demonstrates an alignment of technology with task needs. For example, Convolutional Neural Networks (CNN) is widely used for essential tasks such as forecasting structural integrity (crack prediction), stress detection, and safety measures (detecting safety equipment, evaluating worker postures). RNN is preferred for applications involving activity detection and long-term predictive modeling because of its ability to interpret time-series data. Simpler algorithms, such as KNN and ANN, find use in general classification and detection tasks. This algorithm-to-application mapping demonstrates a detailed grasp of each AI technique's strengths and use cases in the field of construction management.

5. Conclusions

Based on the findings from this paper, Machine Learning has been reported to be used in CEM fields such as Health and Safety, Scheduling, Cost Estimation, Contracts and Conflict Management (Mgt), Supply Chain and Logistics, Site Monitoring & Performance Evaluation, Material Mgt, Offsite Assembly, Plant and Equipment Mgt, Project Planning, Knowledge Mgt, Design, Risk Mgt, Temporary Structures, Bids/Tenders. Whereas Computer Vision is used selectively, and the application of robotics is also found strategically limited. In conclusion, the use of various technologies in CEM reflects a growing inclination towards combining digital and automated solutions. There is a strong preference for machine learning (ML) and computer vision (CV) in tasks that involve analysis and visual processing. Robotics is selectively and strategically employed for physical task execution and risk reduction. Furthermore, Convolutional Neural Networks (CNN) dominate the landscape of Construction Engineering and Management (CEM), being the most frequently referenced algorithm in the dataset. Their popularity highlights their efficiency in image processing and sophisticated pattern recognition tasks, which are critical in a variety of construction applications. In recent years (2019-2020), there has been a considerable shift toward advanced algorithms such as convolutional neural networks (CNN) and recurrent neural networks (RNN). This trend represents a maturing in the industry's approach to AI, as it progresses from foundational algorithms to more sophisticated ones capable of handling complex data and providing deeper insights. This evolution reflects the overall advancement in AI capabilities to handle more complex activities, which necessitates increasingly powerful analytical tools. The authors also note that there is an characteristic crossover between the three technologies since robots utilize Computer Vision (CV) which is in turn powered by Machine Learning (ML) algorithms.

The future work may look at treating secondary literature with Natural Language Processing (NLP) and other text mining approaches to look for clusters of topics, thematic distribution with topical modeling, frequency of terms and terminologies using Pareto Analysis and Word Cloud analysis. Another approach may be to look in the applications of AI and associated technologies deeply and expand the data along with the analysis of the data via protocols grounded in bibliographic and scientometric studies.

References

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges [Review]. *Journal of Building Engineering*, *44*, Article 103299. https://doi.org/10.1016/j.jobe.2021.103299

Abu Kharmeh, S., Natsheh, E., Sulaiman, B., Abuabiah, M., & Tarapiah, S. 2023). Indoor WiFi-Beacon Dataset Construction Using Autonomous Low-Cost Robot for 3D Location Estimation. *Applied Sciences*, *13* 11), 6768.

Ahila Priyadharshini, R., Arivazhagan, S., & Arun, M. (2023). Crack recognition on concrete structures based on machine crafted and hand crafted features.

Akhavian, R., & Behzadan, A. H. (2015). Construction equipment activity recognition for simulation input modeling using mobile sensors and machine learning classifiers. *Advanced Engineering Informatics*, *29*(4), 867-877.

Akhavian, R., & Behzadan, A. H. (2016). Smartphone-based construction workers' activity recognition and classification. *Automation in Construction*, *71*, 198-209.

Akinosho, T. D., Oyedele, L. O., Bilal, M., Ajayi, A. O., Delgado, M. D., Akinade, O. O., & Ahmed, A. A. (2020). Deep learning in the construction industry: A review of present status and future innovations [Review]. *Journal of Building Engineering*, *32*, 14, Article 101827. https://doi.org/10.1016/j.jobe.2020.101827

Alkaissy, M., Arashpour, M., Golafshani, E. M., Hosseini, M. R., Khanmohammadi, S., Bai, Y., & Feng, H. 2023). Enhancing construction safety: Machine learning-based classification of injury types. *Safety Science*, *162*, 106102.

Alsakka, F., El-Chami, I., Yu, H., & Al-Hussein, M. 2023). Computer vision-based process time data acquisition for offsite construction. *Automation in Construction*, *149*, 104803.

Alsugair, A. M., Alsanabani, N. M., & Al-Gahtani, K. S. 2023). Forecasting the Final Contract Cost on the Basis of the Owner's Cost Estimation Using an Artificial Neural Network. *Buildings*, *13* 3), 786.

Anwer, S., Li, H., Umer, W., Antwi-Afari, M. F., Mehmood, I., Yu, Y., Haas, C., & Wong, A. Y. L. 2023). Identification and Classification of Physical Fatigue in Construction Workers Using Linear and Nonlinear Heart Rate Variability Measurements. *Journal of Construction Engineering and Management*, *149* 7), 04023057.

Baduge, S. K., Thilakarathna, S., Perera, J. S., Arashpour, M., Sharafi, P., Teodosio, B., Shringi, A., & Mendis, P. (2022). Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications [Review]. *Automation in Construction*, *141*, 26, Article 104440. https://doi.org/10.1016/j.autcon.2022.104440

Beckman, G. H., Polyzois, D., & Cha, Y.-J. (2019). Deep learning-based automatic volumetric damage quantification using depth camera. *Automation in Construction*, *99*, 114-124.

Cai, S., Ma, Z., Skibniewski, M. J., & Bao, S. (2019). Construction automation and robotics for high-rise buildings over the past decades: A comprehensive review. *Advanced Engineering Informatics*, *42*, 100989.

Chen, W., Li, C., & Guo, H. (2023). A lightweight face-assisted object detection model for welding helmet use. *Expert Systems with Applications*, *221*, 119764.

Chen, Z., & Jiang, C. (2018). Building occupancy modeling using generative adversarial network. *Energy and Buildings*, *174*, 372-379.

Chern, W.-C., Hyeon, J., Nguyen, T. V., Asari, V. K., & Kim, H. (2023). Context-aware safety assessment system for far-field monitoring. *Automation in Construction*, *149*, 104779.

Davies, E. R. (2022). The dramatically changing face of computer vision. In *Advanced Methods and Deep Learning in Computer Vision* (pp. 1-91). Academic Press.

Deng, F., He, Y., Zhou, S., Yu, Y., Cheng, H., & Wu, X. (2018). Compressive strength prediction of recycled concrete based on deep learning. *Construction and Building Materials*, *175*, 562-569.

Dorafshan, S., Thomas, R. J., & Maguire, M. (2018). Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete. *Construction and Building Materials*, *186*, 1031-1045.

Fan, C., Xiao, F., & Zhao, Y. (2017). A short-term building cooling load prediction method using deep learning algorithms. *Applied Energy*, *195*, 222-233.

Fang, Q., Li, H., Luo, X., Li, C., & An, W. (2020). A sematic and prior-knowledge-aided monocular localization method for construction-related entities. *Computer-Aided Civil and Infrastructure Engineering*, *35*(9), 979-996.

Gao, X., Shi, M., Song, X., Zhang, C., & Zhang, H. (2019). Recurrent neural networks for real-time prediction of TBM operating parameters. *Automation in Construction*, *98*, 225-235.

Garcia, J., Villavicencio, G., Altimiras, F., Crawford, B., Soto, R., Minatogawa, V., Franco, M., Martínez-Muñoz, D., & Yepes, V. (2022). Machine learning techniques applied to construction: A hybrid bibliometric analysis of advances and future directions [Review]. *Automation in Construction*, *142*, 22, Article 104532. https://doi.org/10.1016/j.autcon.2022.104532

Gard, N., Chen, J., Tang, P., & Yilmaz, A. (2018). Deep learning and anthropometric plane based workflow monitoring by detecting and tracking workers. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 149-154.

Geng, S., Luo, Q., Liu, K., Li, Y., Hou, Y., & Long, W. 2023). Research status and prospect of machine learning in construction 3D printing. *Case Studies in Construction Materials*, *18*, e01952.

Gong, H., Sun, Y., Mei, Z., & Huang, B. (2018). Improving accuracy of rutting prediction for mechanistic-empirical pavement design guide with deep neural networks. *Construction and Building Materials*, *190*, 710-718.

Hernandez, C., Slaton, T., Balali, V., & Akhavian, R. (2019). A deep learning framework for construction equipment activity analysis. ASCE International Conference on Computing in Civil Engineering 2019, Ivanova, S., Kuznetsov, A., Zverev, R., & Rada, A. (2023). Artificial Intelligence Methods for the Construction and Management of Buildings [Review]. *Sensors (Basel, Switzerland)*, *23*(21). https://doi.org/10.3390/s23218740

Khaitan, S., Gopalakrishnan, K., Choudhary, A., & Agrawal, A. (2017). Deep convolutiona l neural networks with transfer learning for computer vision-based data-drive n pavement distress detection. *Construct. Build. Mater*, *157*, 322-330.

Koch, C., Georgieva, K., Kasireddy, V., Akinci, B., & Fieguth, P. (2015). A review on computer vision based defect detection and condition assessment of concrete and asphalt civil infrastructure. *Advanced Engineering Informatics*, *29*(2), 196-210.

Kolar, Z., Chen, H., & Luo, X. (2018). Transfer learning and deep convolutional neural networks for safety guardrail detection in 2D images. *Automation in Construction*, *89*, 58-70.

LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *nature*, *521*(7553), 436-444.

Lin, P., Wu, M., & Zhang, L. (2023). Probabilistic safety risk assessment in large-diameter tunnel construction using an interactive and explainable tree-based pipeline optimization method. *Applied Soft Computing*, *143*, 110376.

Luo, H., Xiong, C., Fang, W., Love, P. E., Zhang, B., & Ouyang, X. (2018). Convolutional neural networks: Computer vision-based workforce activity assessment in construction. *Automation in Construction*, *94*, 282-289.

Luo, X., Li, H., Cao, D., Dai, F., Seo, J., & Lee, S. (2018). Recognizing diverse construction activities in site images via relevance networks of construction-related objects detected by convolutional neural networks. *J. Comput. Civ. Eng*, *32*(3), 04018012.

Luo, X., Li, X., Goh, Y. M., Song, X., & Liu, Q. (2023). Application of machine learning technology for occupational accident severity prediction in the case of construction collapse accidents. *Safety Science*, *163*, 106138.

Mocanu, E., Nguyen, P. H., Gibescu, M., & Kling, W. L. (2016). Deep learning for estimating building energy consumption. *Sustainable Energy, Grids and Networks*, *6*, 91-99.

Nath, N. D., & Behzadan, A. H. (2017). Construction productivity and ergonomic assessment using mobile sensors and machine learning. In *Computing in civil engineering 2017* (pp. 434-441).

Nath, N. D., Behzadan, A. H., & Paal, S. G. (2020). Deep learning for site safety: Real-time detection of personal protective equipment. *Automation in Construction*, *112*, 103085.

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, *83*, 121-139.

Oke, A. E., Aliu, J., Fadamiro, P. O., Akanni, P. O., & Stephen, S. S. (2023). Attaining digital transformation in construction: An appraisal of the awareness and usage of automation techniques. *Journal of Building Engineering*, *67*, 105968.

Ottoni, A. L., Novo, M. S., & Costa, D. B. (2023). Deep Learning for vision systems in Construction 4.0: a systematic review. *Signal, Image and Video Processing*, *17* 5), 1821-1829.

Oyedele, A. O., Ajayi, A. O., & Oyedele, L. O. (2021). Machine learning predictions for lost time injuries in power transmission and distribution projects. *Machine Learning with Applications*, *6*, 100158.

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, *122*, 103517.

Poh, C. Q., Ubeynarayana, C. U., & Goh, Y. M. (2018). Safety leading indicators for construction sites: A machine learning approach. *Automation in Construction*, *93*, 375-386.

Rafiei, M. H., & Adeli, H. (2016). A novel machine learning model for estimation of sale prices of real estate units. *Journal of Construction Engineering and Management*, *142*(2), 04015066.

Rafiei, M. H., & Adeli, H. (2018). Novel machine-learning model for estimating construction costs considering economic variables and indexes. *Journal of Construction Engineering and Management*, *144*(12), 04018106.

Rahimian, F. P., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, *110*, 103012.

Rahman, A., & Smith, A. D. (2018). Predicting heating demand and sizing a stratified thermal storage tank using deep learning algorithms. *Applied Energy*, *228*, 108-121.

Rahman, A., Srikumar, V., & Smith, A. D. (2018). Predicting electricity consumption for commercial and residential buildings using deep recurrent neural networks. *Applied Energy*, *212*, 372-385.

Ramadan, A. S., & Elgendi, E. O. (2023). A review of optimization techniques and algorithms used for FRP applications in civil engineering. *Journal of Engineering and Applied Science*, *70* 1), 1-49.

Rashid, K. M., & Louis, J. (2019). Times-series data augmentation and deep learning for construction equipment activity recognition. *Advanced Engineering Informatics*, *42*, 100944.
Rashidi, A., Sigari, M. H., Maghiar, M., & Citrin, D. (2016). An analogy between various machine-learning techniques for detecting construction materials in digital images. *KSCE Journal of Civil Engineering*, *20*, 1178-1188.
Sadatnya, A., Sadeghi, N., Sabzekar, S., Khanjani, M., Tak, A. N., & Taghaddos, H. 2023). Machine learning for construction crew productivity prediction using daily work reports. *Automation in Construction*, *152*, 104891.
Sánchez-Garrido, A. J., Navarro, I. J., García, J., & Yepes, V. 2023). A systematic literature review on modern methods of construction in building: An integrated approach using machine learning. *Journal of Building Engineering*, 106725.
Schmidhuber, J. (2015). Deep learning in neural networks: An overview. *Neural networks*, *61*, 85-117.
Sherafat, B., Rashidi, A., & Song, S. (2020, March). A Software-Based Approach for Acoustical Modeling of Construction Job Sites with Multiple Operational Machines. In *Construction Research Congress 2020* (pp. 886-895). Reston, VA: American Society of Civil Engineers.
Singaravel, S., Suykens, J., & Geyer, P. (2018). Deep-learning neural-network architectures and methods: Using component-based models in building-design energy prediction. *Advanced Engineering Informatics*, *38*, 81-90.
Slaton, T., Hernandez, C., & Akhavian, R. (2020). Construction activity recognition with convolutional recurrent networks. *Automation in Construction*, *113*, 103138.
Tixier, A. J.-P., Hallowell, M. R., Rajagopalan, B., & Bowman, D. (2016). Application of machine learning to construction injury prediction. *Automation in Construction*, *69*, 102-114.
Wang, J., & Ashuri, B. (2017). Predicting ENR construction cost index using machine-learning algorithms. *International Journal of Construction Education and Research*, *13*(1), 47-63.
Wang, J., Shou, W., Wang, X., & Wu, P. (2016). Developing and evaluating a framework of total constraint management for improving workflow in liquefied natural gas construction. *Construction Management and Economics*, *34*(12), 859-874.
Wang, L., Zhao, Z.-k., & Xu, N. (2015). Deep Belief Network Based 3D Models Classification in Building Information Modeling. *International Journal of Online Engineering*, *11*(5).
Wang, S., Ma, Q., & Liang, H. 2023). System simulation of land use spatial planning method and environment management strategy analysis by using machine vision. *Soft Computing*, *27* 9), 5985-5994.
Wang, Y., Dai, F., Jia, R., Wang, R., Sharifi, H., & Wang, Z. (2023). A novel combined intelligent algorithm prediction model for the tunnel surface settlement. *Scientific Reports*, *13* 1), 9845.
Wen, H., Liu, L., Zhang, J., Hu, J., & Huang, X. (2023). A hybrid machine learning model for landslide-oriented risk assessment of long-distance pipelines. *Journal of Environmental Management*, *342*, 118177.
Wiley, V., & Lucas, T. (2018). Computer vision and image processing: a paper review. *International Journal of Artificial Intelligence Research*, *2*(1), 29-36.
Wu, J., Cai, N., Chen, W., Wang, H., & Wang, G. (2019). Automatic detection of hardhats worn by construction personnel: A deep learning approach and benchmark dataset. *Automation in Construction*, *106*, 102894.
Wu, X., Lu, G., & Wu, Z. (2023). Remote Sensing Technology in the Construction of Digital Twin Basins: Applications and Prospects. *Water*, *15* 11), 2040.
Xu, Y., Zhou, Y., Sekula, P., & Ding, L. (2021). Machine learning in construction: From shallow to deep learning. *Developments in the Built Environment*, *6*, 100045.
Yang, K., Ahn, C. R., & Kim, H. (2020). Deep learning-based classification of work-related physical load levels in construction. *Advanced Engineering Informatics*, *45*, 101104.
Yu, Y., Li, H., Yang, X., Kong, L., Luo, X., & Wong, A. Y. (2019). An automatic and non-invasive physical fatigue assessment method for construction workers. *Automation in Construction*, *103*, 1-12.
Zhang, H., Yan, X., & Li, H. (2018). Ergonomic posture recognition using 3D view-invariant features from single ordinary camera. *Automation in Construction*, *94*, 1-10.
Zhang, L., Yao, H., Fu, Y., & Chen, Y. (2023). Comparing Subjective and Objective Measurements of Contract Complexity in Influencing Construction Project Performance: Survey versus Machine Learning. *Journal of Management in Engineering*, *39* 4), 04023017.
Zhang, T., Lee, Y.-C., Scarpiniti, M., & Uncini, A. (2018). A supervised machine learning-based sound identification for construction activity monitoring and performance evaluation. Construction Research Congress 2018,
Zou, M., Yu, J., Lv, Y., Lu, B., Chi, W., & Sun, L. 2023). A Novel Day-to-Night Obstacle Detection Method for Excavators based on Image Enhancement and Multi-sensor Fusion. *IEEE Sensors Journal*.