LEVERAGING CIRCULAR ECONOMY APPLICATIONS IN THE OFFSITE CONSTRUCTION SECTOR THROUGH ARTIFICIAL INTELLIGENCE: A SCIENTOMETRIC REVIEW

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Offsite construction (OSC) offers a sustainable approach to building, employing innovative methods to reduce waste and enhance delivery efficiency. Integrating circular economy (CE) principles into OSC can further improve its circularity performance, fostering a more sustainable environment. More so, artificial intelligence (AI) can accelerate this integration, augmenting CE application capabilities in OSC. Despite the extensive literature on OSC and CE, implementing AI to enable the integration of CE and OSC, or CE in OSC, remains underexplored. The review aims to analyse the convergence of these domains, uncovering insights for advancing sustainable OSC practices. This research employed scientometric and qualitative analysis to assess 619 journal articles on AI, CE, and OSC literature. Science mapping quantitative literature review and visualisation techniques were used to investigate the data, determining frequently discussed concepts. The evaluation details AI's integration of CE and OSC, summarising primary applications and limitations. A framework highlighting AI's potential for promoting CE practices in OSC was developed. The findings highlight AI-machine learning models that overcome the synergy barriers of CE and OSC and serve as a benchmark for future studies.

Keywords: Artificial Intelligence; circular economy; offsite construction

INTRODUCTION

The construction industry has long been the subject of criticism and debate due to its performance and environmental impact – it is one of the largest consumers of natural resources as an industry (Illankoon and Vithanage, 2023). However, in response to these persistent challenges, industry professionals and regulatory bodies have made collective efforts to introduce innovative methods. Offsite construction (OSC) and circular economy (CE) have been identified as alternatives and promising strategies for promoting sustainable development and resource management within the construction industry (Obi et al., 2022).

OSC is an umbrella term encapsulating many construction types or processes that do not occur on the final building site. Unlike traditional construction methods, OSC

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involves a process from planning to fabricating or assembling substantial construction parts at a factory for the rapid and efficient construction of permanent structures (Smith and Quale, 2017). The construction industry has benefitted from OSC immensely through shortened construction processes, waste minimisation and enhanced quality (Goulding and Rahimian, 2019). One essential requirement of OSC is to improve the sustainability of construction projects and the industry through its supply chains. OSC methods that allow for the easy assembly and disassembly of building components, for example, present leveraging opportunities for CE applications in OSC processes for enhanced OSC products and opportunities to contribute to sustainable systems (Illankoon and Vithanage, 2023).

The notion of CE has become increasingly prominent on the agendas of policymakers and essential fields of academia worldwide (Geissdoerfer et al., 2017) due to its capacity to address issues surrounding sustainable development, waste generation, and resource maximisation by designing a waste-free and regenerative system (EMF, 2019). The CE emphasises designing manufactured products to incorporate added value and maximise utility in longer life cycles (Ellen MacArthur Foundation, 2019).

CE applications have been identified in literature through frameworks such as ReSOLVE and the R-imperatives for resource management and effective design practices (Pomponi and Moncaster, 2017). The construction industry is not an exception. Even though the synergy between CE and OSC enhances sustainable practice, several pitfalls barricade their integration (design and planning complexity, material sourcing and management, economic viability and quality control and standardisation). However, the Ellen MacArthur Foundation (2019) argues that artificial intelligence (AI) is a vital technology that can potentially help the systemic shift in opposing the linear economy model and facilitate CE integration in organisational systems.

AI is the so-called umbrella term for a collection of technological applications that enables computers and machines to simulate the human brain and problem-solving capabilities in performing tasks. AI provides data-driven solutions through pattern recognition, prediction, optimisation, and recommendation generation capabilities based on data from videos, images, audio, numeric, and text (EMF, 2019). AI has proven to effectively analyse substantial data from organisational processes to improve them further when combined with expert knowledge principles. Van de Aalst et al. (2023) firm their argument that AI offers capabilities for identifying opportunities for improving circularity performances within systems.

Given the growing interest in integrating AI with CE for OSC, numerous reviews have synthesised research in this domain (Wang et al., 2020; Obi et al., 2022; Alsakka et al., 2023; Lee et al., 2022; Pan et al., 2022; Liu et al., 2022; Illankoon and Vithanage, 2023). However, there is a notable scarcity of research examining the intersection of AI, CE, and OSC for strategic advantages of OSC and CE integration and overcoming integration pitfalls for enhanced synergies. Furthermore, the extent of these relationships remains unclear in existing studies. This study seeks to fill the gap by providing insights into AI models that potentially contribute to overcoming integration pitfalls for improving circularity practices in OSC supply chain processes.

Employing scientometric and qualitative analysis techniques, the study examines existing research on using AI models in facilitating strategic CE initiatives within OSC. The study aims to analyse the convergence of CE, OSC and AI to uncover insights for advancing sustainable OSC. To achieve this aim, the review looked at the following objectives: (1) to identify the leading countries and journals publishing in the fields of AI, CE and OSC, (2) to visualise the current research interconnection among AI, CE and OSC concepts (3) to identify AL models that support the integration of CE and OSC. The study intends to offer insights into applying AI models for CE initiatives in OSC activities for multiple stakeholders.

METHOD

The study employs integrated quantitative and qualitative analysis methods to critically evaluate the literature on AI models to enhance CE in the OSC sector. Figure 1 depicts the methodological approach used in the investigation.

Stage 1 - Search for Publications and Screening

Proper keyword search is a crucial success factor in a scientometric analysis. We borrowed the search keywords for CE, OSC and AI from bibliometric and literature review studies by Obi et al. (2022) and Oluleye et al. (2022), who selected keywords to integrate the concepts. A search code combining keywords highlighted in their studies was used with the query string being:

(“Off-site construction” OR “off site construction” OR “prefabricated construction” OR “industrialised building” OR “panelised construction” OR “modular construction” OR “tilt up construction” OR “offsite construction” OR “precast construction” OR "tilt-up construction" OR "off site manufacturing" OR "prefabrication construction" OR “Circularity” OR “circular economy and construction”) AND (“digitalisation” OR “deep learning” OR “Big Data” OR “Artificial Intelligence” OR “machine learning” OR “robotics” OR “artificial neural network” OR “digital technology” OR “sensor” OR “computer vision” OR “image processing”)

The search string could be summarised as "OSC" OR "CE" AND "AI". This search string was selected due to the scarcity of information on a search string encompassing all three concepts. The keywords used produced 2,471 publications from Scopus. The database was screened for relevance, language, and quality against inclusion criteria outlined in “Stage 1” of Figure 1.

Stage 2 - Scientometric Analysis

The study used VOSviewer software to perform a visualisation analysis of citations and co-occurrences to extract relevant data based on objectives 1 and 2.

Stage 3 - Qualitative Analysis

A qualitative analysis of carefully selected papers was conducted at this stage (as illustrated in Figure 1). Additional selection criteria were implemented to identify pivotal research articles for content analysis. The criteria focused on journal articles related to building construction, explicitly exploring AI applications in OSC elements or CE strategies or both concepts, with relevant keywords in titles and abstracts (Figure 1). Consequently, 31 articles met these criteria and were chosen for in-depth qualitative review.

This analysis was modelled after the methodologies of Oluleye et al. (2022) and Rodrigo et al. (2024), serving as a qualitative supplement to the scientometric analysis. It aimed to identify AI-machine learning models that support OSC elements or CE strategies in alignment with the study’s third objective. Due to the current nature of the paper and space limitations, references for each analysed article were not included.

FINDINGS AND DISCUSSION

Scientometric Analysis

This section presents the findings from the scientometric analysis conducted in this study, addressing objectives 1 and 2.

Citation Analysis

Studies, according to Obi et al. (2022) argue that the number of publications and citations can determine the impact and quality of an area of study. The citation analysis employed sources and countries to pinpoint leading countries and journals in OSC, CE, and AI research areas.

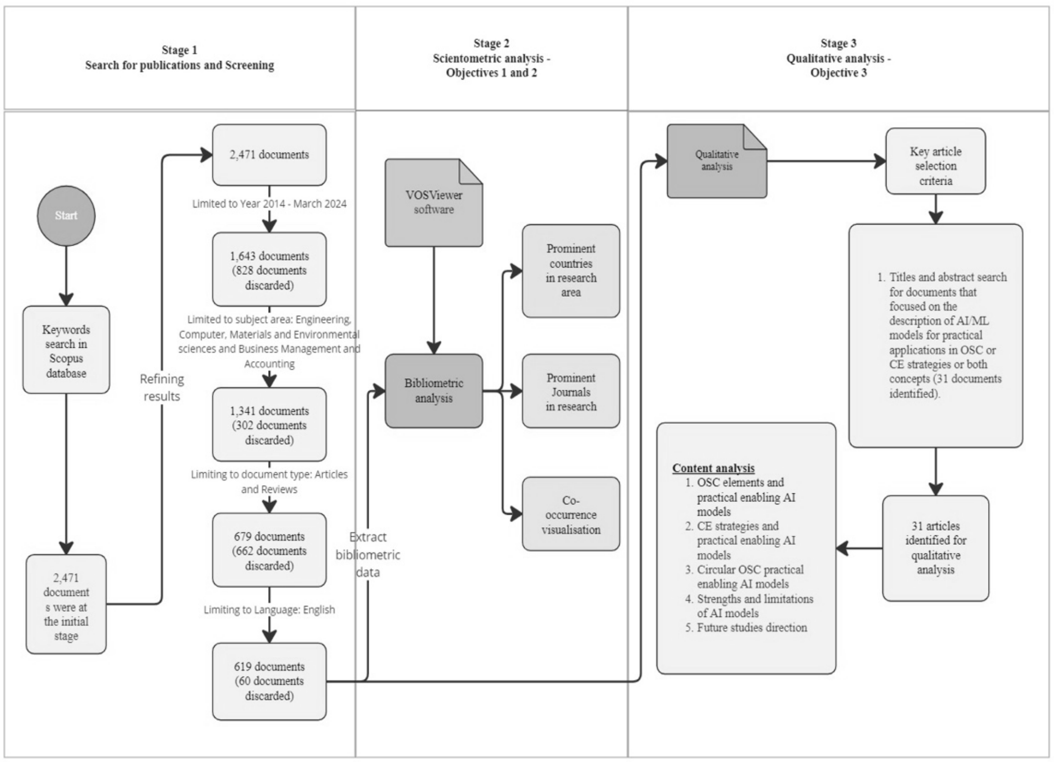


Figure 1: Research methodology overview

Countries in CE, OSC and AI research.

This section established a threshold of at least five documents and ten citations using VOSviewer software version 1.6.20 to ensure the inclusion of only actively participating countries in the research context. The analysis revealed that only 33 out of 72 countries met this threshold.

Results further indicated that the most recent publications are from Finland, Norway, Hong Kong, and Italy, suggesting that the study trends are predominantly within the global north. Among the leading countries, China has the highest number of publications (156 publications, 2,811 citations), followed by the United States (73 publications, 2,305 citations) and the United Kingdom (71 publications, 1,667 citations).

Scholarly contributions from the global north significantly outnumber those from the global south, potentially due to the constrained financial resources and lower publications on adopting innovation and technology in the latter. However, the increasing number of CE and OSC field studies emphasises the need for collaborative efforts to advance research and practice in CE, OSC, and AI.

Leading Journals in CE, OSC and AI research.

Journals play a significant role in advancing knowledge, disseminating research findings, and establishing trends in the academic community. In VOSviewer, a minimum threshold of five publications was set; out of 368 sources, only 17 met this criterion. Leading journals include Automation in Construction (36 publications, 1447 citations), Sustainability (Switzerland) (25 publications, 309 citations), Journal of Cleaner Production (14 publications, 435 citations), Buildings, IEEE Access, International of Advanced Manufacturing Technology, and Journal of Construction Engineering and Management (each with 11 publications and 200, 100, 113, and 149 citations respectively). The most recent publications are in Sustainable Production and Consumption and the Journal of Building Engineering. These results indicate that journals have broadened their scope to include OSC and CE, focusing on sustainable Development, Efficient Resource Utilisation, and Construction Lifecycle Management.

Co-Occurrence Analysis of CE, OSC and AI Research

The analysis was performed using “all keywords” as the unit of analysis, with a minimum threshold of 25 occurrences for inclusion. Repeated terms, such as “ANN” and “artificial neural network”, were merged. Of the 7,149 keywords, 27 met the threshold, but only 23 were used after excluding generic terms like humans, construction industry, and articles. The results further indicate that numerous OSC, CE and AI papers were published between 2020 and 2022. The findings also suggest that digital technologies, sustainability, CE, and machine learning (ML) literature have recently garnered more attention than OSC literature. This trend aligns with the focus on data-informed decisions and solutions to enhance circularity and sustainability in the research area.

Qualitative Analysis

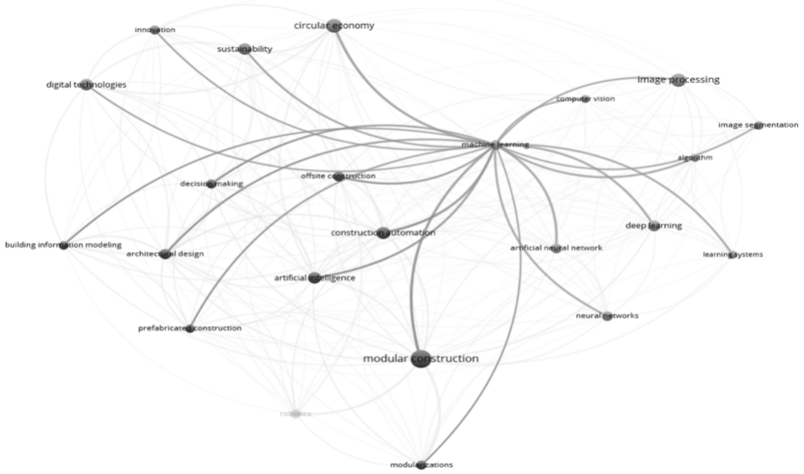
VOSviewer software helped to give a general view of the most used theories, concepts, and models in the research area. However, these details may not be conclusive enough based on the study’s objectives; hence, this section presents a content analysis of carefully selected articles to provide a more comprehensive analysis to address objective 3 of the study (Figure 1).

AI Potentials for Promoting CE Applications in OSC

This section describes the general roles of AI-machine learning models for OSC elements and CE applications in the construction industry. Data from the 31 identified articles were screened against specific inclusion criteria (mentioned in stage 3 of the method and Figure 1). The critical review indicated that out of the 31 articles, only 21 (57%) investigated AI for OSC, 9 articles (24%) touched on AI for CE, and 1 article (3%) investigated AI, CE, and OSC combined.

Referring to the visualisation diagram of Figure 2, it is evident that studies have highlighted machine learning as a component of AI that interconnects with various aspects of CE and OSC. Like a study by Pan et al. (2022), AI-machine learning is considered an influential and promising tool when combined with expert knowledge for evaluating and assisting in data-informed decisions related to OSC and CE or combined applications to strengthen potential areas for increased circularity performance within OSC organisations.

Figure 2: All Keywords co-occurrence of Machine learning (ML)



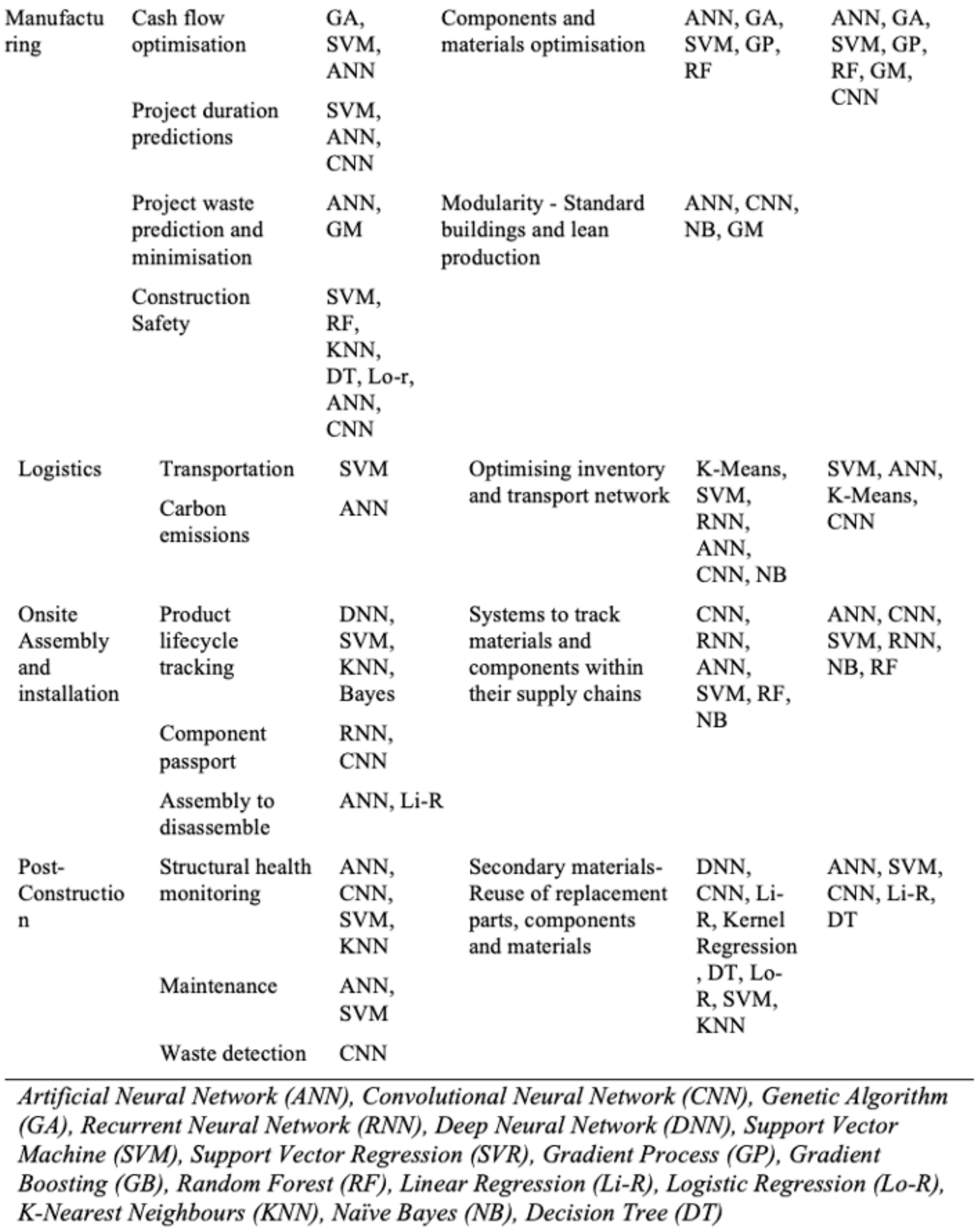
This, therefore, became a basis for further thorough examination of the 31 articles that met the criteria. From these articles, fourteen AI-machine learning models were identified to augment OSC elements and CE strategies, as well as commonly used machine learning models for these combined activities for strategic circular manufacturing. The results identified are summarised in Table 1.

Strengths and Limitations of machine learning models for enabling circularity in OSC.

The application of machine learning to enhance CE applications in OSC holds significant promise for advancing sustainability and resource efficiency. Despite their capabilities, respective strengths and limitations were identified in the literature review and summarised in Table 2. Table 3 further outlines prospective future research on machine learning models, aiming to leverage advanced machine learning models for CE applications within the OSC sector.

Table 1: Potential enabling AI-machine learning models for CE and OSC integration

OSC processes	OSC elements	Enabling AI models	CE strategies	Enabling AI models	AI Models Enabling CE and OSC Integration (Proposed)
Design	Architectural and structural designs and visualisation.	ANN, CNN	Design for assembly and disassembly.	ANN, Li-R, GA	ANN, GA, GB, GP, RF, SVM, Li-R, DT
			Design for adaptability/ flexibility.	ANN, GA, GP, RF, SVM,	
			Durability - Design for the long performance lifespan of components and materials	RNN, GP, DT, GB, SVM	
	Appropriate materials selection	ANN, SVM, KNN, CNN, RF, Li-R, DT, NB	Circular materials selection/ substitution	ANN, GB, GP	



Manufacturing	Cash flow optimisation	GA, SVM, ANN	Components and materials optimisation	ANN, GA, SVM, GP, RF	ANN, GA, SVM, GP, RF, GM, CNN
	Project duration predictions	SVM, ANN, CNN			
	Project waste prediction and minimisation	ANN, GM	Modularity - Standard buildings and lean production	ANN, CNN, NB, GM	
	Construction Safety	SVM, RF, KNN, DT, Lo-r, ANN, CNN			
Logistics	Transportation	SVM	Optimising inventory and transport network	K-Means, SVM, RNN, ANN, CNN, NB	SVM, ANN, K-Means, CNN
	Carbon emissions	ANN			
Onsite Assembly and installation	Product lifecycle tracking	DNN, SVM, KNN, Bayes	Systems to track materials and components within their supply chains	CNN, RNN, ANN, SVM, RF, NB	ANN, CNN, SVM, RNN, NB, RF
	Component passport	RNN, CNN			
	Assembly to disassemble	ANN, Li-R			
Post-Construction	Structural health monitoring	ANN, CNN, SVM, KNN	Secondary materials- Reuse of replacement parts, components and materials	DNN, CNN, Li-R, Kernel Regression, DT, Lo-R, SVM, KNN	ANN, SVM, CNN, Li-R, DT
	Maintenance	ANN, SVM			
	Waste detection	CNN			

Artificial Neural Network (ANN), Convolutional Neural Network (CNN), Genetic Algorithm (GA), Recurrent Neural Network (RNN), Deep Neural Network (DNN), Support Vector Machine (SVM), Support Vector Regression (SVR), Gradient Process (GP), Gradient Boosting (GB), Random Forest (RF), Linear Regression (Li-R), Logistic Regression (Lo-R), K-Nearest Neighbours (KNN), Naïve Bayes (NB), Decision Tree (DT)

CONCLUSION

The study was conducted in two phases to achieve its objectives. First, a scientometric analysis of 619 articles from the Scopus database was performed to address objectives 1 and 2. This analysis identified leading countries and journals and the interconnections among AI, CE, and OSC. It highlighted the pivotal role of AI-machine learning in enhancing CE concepts and the broader OSC scope, forming the foundation for the subsequent qualitative analysis. Using the Scopus data and additional selection criteria (as depicted in Figure 1), relevant articles were selected for content analysis to address objective 3.

The qualitative analysis identified AI-machine learning models from previous studies that facilitate OSC elements and CE strategies. We then identified 14 AI-machine learning models commonly used for their activities to overcome pitfall integrations. The review also revealed gaps in the literature, showing that most studies are concentrated in the global north, like Europe and America, with the global south lagging in AI adoption based on the articles published. More research is needed to provide equitable development opportunities for the global south. Despite the study's valuable contribution, it is essential to acknowledge its limitations when interpreting the findings.

Table 2: AI models Enabling CE and OSC integration, Strengths, limitations, and future studies

ML model	Strengths	Limitations	Further studies
ANN	1. Ability to predict materials for circularity. 2. Ability to support circular designs for modularity.	1. Poor ability to be interpreted by professionals without IT skills. 2. Lack of data on circularity prediction in the OSC sector	To investigate platforms for collating datasets to enable circular predictions.
CNN	1. Excels at image data recognition and analysis for recycling, remanufacturing, or reusing materials within CE frameworks.	1. Prone to class imbalance 2. Limited generalisation ability	To explore techniques to improve CNN's data training and generalisation capabilities for CE applications and predictions
GA	1. Can discover acceptable optimising solutions for complex problems for circularity designs.	1. Complexity of OSC and CE data would require significant computational resources and time.	To explore hybrid models combining GA with other models for efficient and effective CE optimisation for OSC.
RNN	1. Adaptability to diverse data types for comprehensive analysis of CE strategies. 2. Predictive capabilities for materials demand, waste generation and resource optimisation.	1. An extensive dataset on circularity predictions within OSC processes is required. 2. Poor ability to be interpreted by professionals without IT skills.	To investigate platforms for a straightforward interpretation of RNN models for CE applications.
SVM/ SVR	1. Performs well in analysing complex datasets for circularity applications.	1. The "black box" character of SVM/SVR predictions is challenging to understand	To investigate platforms for straightforward interpretations of SVM/SVR models for circular predictions.
GB	1. Enhanced prediction accuracy	1. Overfitting concerns. 2. Prone to class imbalance.	
RF	1. Robustness to overfitting while maintaining predictive accuracy	1. RF predictions' "black box" character is challenging to understand	To investigate platforms for a straightforward interpretation of RF models.

Table 3: Strengths, limitations, and future studies for machine learning models leveraging CE in the OSC sector

ML model	Strengths	Limitations	Further studies
GP	1. Flexible, versatile, and capable of predicting circular materials, waste generation and resource optimisation. 2. Ability to accommodate large and complex datasets.	1. Relies heavily on quality datasets for training and validation for optimum predictions.	To investigate platforms for collating datasets to enable circular predictions.
DT	1. Ability to predict the strength of circular materials. 2. Easy to interpret and explain.	1. Susceptible to overfitting - may capture other data rather than the underlying patterns during data training.	To explore hybrid models combining DT with other models for efficient and effective CE outcomes.

The analysis was based on only Scopus (i.e., a single database), potentially limiting the coverage of publications in the study area. Furthermore, the study was restricted to journal articles. It may benefit future research to incorporate multiple databases and diverse document types to improve the study. Additionally, the literature search used specific keywords, which may have overlooked other relevant keywords. Future studies may broaden the scope by including additional keywords.

The study's findings intend to serve multiple stakeholders. The study identified potential future research directions for academic scholars. For policymakers, the results provide valuable insights into AI-machine learning models to apply for OSC and CE synergies, elucidating their potential areas of applicability for strategic OSC activities. Nevertheless, investigations into AI-machine learning for enhancing CE in OSC are incipient. Subsequent studies should concentrate on future research pathways, especially for ANN, CNN and SVM/SVR models identified in Table 2, to foster AI-machine learning models and expert knowledge combinations for strengthened circular systems within OSC supply chain management.

By integrating AI-driven circularity practices into OSC, advancements can be made towards achieving some Sustainable Development Goals (SDGs), such as SDGs 9 and 12, by enhancing resource efficiency, reducing waste, and fostering innovation in construction practices. For example, using AI to optimise material usage reduces waste and improves resource efficiency. Moreover, the study was conducted at the OSC process level to identify AI-machine learning models, which can augment CE principles in potential areas of the OSC sector when combined with expert knowledge. Future studies can also be done at the product and management levels.

REFERENCES

Alsakka, F, Assaf, S, El-Chami, I and Al-Hussein, M (2023) Computer vision applications in offsite construction, *Automation in Construction*, **154**, 104980.

Ellen MacArthur Foundation (2019) *Artificial Intelligence and the Circular Economy: AI as a Tool to Accelerate the Transition*, New York: Ellen MacArthur Foundation.

Goulding, J S and Rahimian, F P (Eds) (2019) Offsite manufacturing: envisioning the future agenda, *In*: *Offsite Production and Manufacturing for Innovative Construction*, Abingdon: Routledge, 1-22.

Illankoon, C and Vithanage, S C (2023) Closing the loop in the construction industry: A systematic literature review on the development of circular economy, *Journal of Building Engineering*, **76**, 107362.

Lee, S, Jeong, M, Cho, C S, Park, J and Kwon, S (2022) Deep learning-based pc member crack detection and quality inspection support technology for the precise construction of OSC projects, *Applied Sciences*, **12**(19).

Liu, C, M E Sepasgozar, S, Shirowzhan, S and Mohammadi, G (2022) Applications of object detection in modular construction based on a comparative evaluation of deep learning algorithms, *Construction Innovation*, **22**(1), 141-159.

Obi, L, Arif, M, Daniel, E I, Oladinrin, O T and Goulding, J S (2022) Establishing underpinning concepts for integrating circular economy and offsite construction: a bibliometric review, *Built Environment Project and Asset Management*, **13**(1), 123-139.

Oluleye, B I, Chan, D W and Antwi-Afari, P (2022) Adopting Artificial Intelligence for enhancing the implementation of systemic circularity in the construction industry: A critical review, *Sustainable Production and Consumption*, **35**, 509-524.

Pan, M, Yang, Y, Zheng, Z and Pan, W (2022) Artificial Intelligence and robotics for prefabricated and modular construction: A systematic literature review, *Journal of Construction Engineering and Management*, **148**(9), 03122004.

Pomponi, F and Moncaster, A (2017) Circular economy for the built environment: A research framework, *Journal of Cleaner Production*, **143**, 710-718.

Rodrigo, N, Omrany, H, Chang, R and Zuo, J (2024) Leveraging digital technologies for circular economy in the construction industry: A way forward, *Smart and Sustainable Built Environment*, **13**(1), 85-116.

Smith, R E and Quale, J D (2017) *Offsite Architecture: Constructing the Future*, London: Taylor & Francis.

Van der Aalst, W M P, Hinz, O and Weinhardt, C (2023) Sustainable Systems Engineering, *Business and Information Systems Engineering*, **65**(1), 1-6.

Wang, M, Wang, C C, Sepasgozar, S and Zlatanova, S (2020) A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0, *Buildings*, **10**(11), 204.