2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

CURRENT PRACTICES IN CO_2 TRACKING FOR THE CONSTRUCTION STAGE IN EUROPE: ADVANCEMENTS, CONSTRAINTS, AND RECOMMENDATIONS

Jhonattan G. Martinez[1], Patrick Montanari[1], Saijal Singhal[1], Luis Alva[1], Timson Yeung[2], and Freddy Mantilla[3]

[1]Aarhus University, Denmark

[2] Technion, Haifa, Israel,

[3] The Cooperative University of Colombia

Abstract

Recent technological advancements and methods for CO_2 tracking within construction have enhanced emissions monitoring. However, traditional CO_2 tracking methods often rely on manual processes lacking real-time capabilities, limiting their effectiveness in offering solutions for reducing emissions. This study uses a literature review and expert opinions to examine current practices and advancements in CO_2 tracking for the construction sector, evaluating their effectiveness and potential for broad industry adoption based on European Union regulations. Ultimately, this work contributes to the advancement of CO_2 monitoring by providing recommendations that meet regulatory requirements, and stakeholder demands for sustainable construction practices in the future.

Introduction

Several studies have proven that construction represents one of the most resource-intensive sectors of human activity. It is responsible for using 40% of the available resources and produces about 21% of world's gas emissions (IPCC, 2022). To mitigate this, the European Union (EU) has introduced a series of regulations and directives to enforce stricter control and monitoring of CO2 emissions during construction as part of its overarching climate goals, including the European Green Deal (European Commission, 2021). These policies address the impact of carbon emissions not only during the operational life of buildings but also throughout the construction process, addressing embodied carbon. However, current methodologies and practices in the construction sector face significant challenges in meeting these standards. Key barriers include the lack of standardised and accurate real-time emissions monitoring systems, limited integration of digital tools such as Building Information Modelling (BIM) and Internet of Things (IoT) technologies, and insufficient adoption of low-carbon materials (Chen et al., 2021).

Two types of assessment are usually implemented to compute embodied emissions in the construction stage: theoretical estimations based on Life Cycle Assessment (LCA) or activity monitoring, either through historical data or real-time information. Currently, most studies involving IoT sensors only consider their theoretical use due to the implementation cost; they can accurately measure CO2 emissions in real time and monitor machines' efficiency and operational states. This represents an important knowledge gap that needs to be filled using new technologies. Machine learning (ML), specifically applying statistical models to predict and forecast emissions through machine activity pattern analyses, is useful for performing such operations and discovering ways to optimise activity times and reduce the engine hours required to perform the assigned tasks.

This study aims to offer insights into current practices and theoretical frameworks related to assessing CO2 emissions in the construction stage. Building on recent advancements in the field, its primary contribution lies in identifying key challenges in acquiring real-time data and providing recommendations for achieving target levels by European regulations. Significant constraints associated with currently available knowledge and technologies are examined based on recent publications and expert opinions consulted during the research process. This approach aims to provide a comprehensive understanding of the limitations that hinder the effective implementation of CO2 monitoring and reduction strategies in the construction stage while also identifying gaps in existing frameworks and potential areas for future innovation.

Methodology

To develop effective solutions for sustainability, it is crucial to assess the current state of CO2 tracking in the construction industry. This study builds upon a critical literature review using the ROSES (RepOrting standards for Systematic Evidence Syntheses) (Haddaway et al. 2018) procedure. The review identifies publications that propose solutions or design strategies for monitoring CO2 emissions during construction activities. The paper selection was limited to the material transportation and constructionstages of a building's life cycle to maintain a clear and targeted scope. By narrowing the focus to these critical stages, the study aims to provide actionable insights and strategies for mitigating CO2 emissions in construction.

The main keywords chosen were "carbon emissions," "construction," and "monitoring." Papers published before 2018 were discarded unless they were worth considering and had already been cited in the more recent ones. Only 48 peer-reviewed articles and conference papers written in English were selected. During the final stage of the screening process, a full-text review was conducted to evaluate the individual relevance of this study. While going through the process, 10 articles were excluded as they lacked significant contributions to the design or application of carbon emission monitoring systems strategies, basing their assumptions on pre-existing designs. After proper filtering, 19 papers were selected, as their contribution aligned with the topic of discussion; only the most relevant ones will be mentioned in the text.

Finally, the Delphi method was utilised to gather insights from four construction industry experts in LCA analysis, construction management, and monitoring technologies. The criteria for selection were their academic publications, project experience, and professional roles in the fields of construction sustainability and digital monitoring. The four experts selected for the study each have over 10 years of experience in the fields of construction and sustainability. Specifically, (1) a senior consultant in LCA focused on embodied carbon, (2) a professor of construction management specialising in digital technologies and emissions monitoring, an (3) industry professional experienced in IoT-based solutions for heavy equipment tracking, and (4) a project manager responsible for digital implementation strategies and ensuring compliance with EU sustainability regulations.

Two rounds of structured consultation were followed to document the constraints and recommendations related to CO_2 tracking for the construction stage. The first round involved open-ended questionnaires to identify perceived barriers, constraints, and possible solutions. The second round was used to refine and validate the themes that emerged in the first round. Experts were asked to comment on a consolidated list of constraints and recommendations. The study concluded when a consensus threshold of 80% agreement among the panel was reached regarding the relevance and criticality of the identified challenges and recommendations. Consensus was established through qualitative thematic analysis, which converged across the two rounds, where experts analysed the written responses to identify common themes, opinions, and patterns in their feedback.

Literature Review

European Union regulations on CO2 emissions

The European Union has implemented a series of regulations to reduce CO2 emissions in the construction sector, aiming to achieve climate neutrality by 2050. Some regulations, such as the Energy Performance of Buildings Directive (European Commission, 2015), focus on enhancing the energy efficiency of buildings throughout their lifecycle, including the construction phase. Circular economy principles are promoted by encouraging the use of sustainable materials, recycling, and reducing waste in construction. Additionally, the Renovation Wave Initiative aims to enhance energy efficiency in buildings through large-scale renovations, thereby supporting the EU's circular economy objectives. These measures are part of the broader European Green Deal (European Commission, 2021), which encompasses various strategies and regulations aimed at making Europe climate-neutral by 2050.

EU regulations emphasise the need for stringent monitoring and reporting of CO2 emissions, particularly during the construction stage, as part of the broader strategy to achieve carbon neutrality by 2050. A key aspect of this regulatory push is the promotion of digitalisation, including the use of advanced tools, such as IoT sensors and BIM, to enhance the accuracy and efficiency of CO_2 control.

Theoretical frameworks for CO2 calculation

LCA analysis usually adopts one of two main approaches (Dixit M.K., 2017): bottom-up (process-based) or top-down (input-output analysis). The first calculates emission amounts by multiplying material quantity and carbon factor, while the second multiplies cost by intensity. are flawed: process-based methods are not accurate and often underestimate output values, while input-output methods are often too generalized (Chen et al., 2021). Many authors suggest adopting a hybrid approach, integrating these two in a single assessment analysis (Zhang et al., 2020).

While LCA-based analysis may provide assessments of emissions over the whole building's life cycle and do not implement tools for reducing emissions by taking corrective actions (Chung et al., 2024). Empirical research papers used a wide range of approaches to calculate the real emissions through approximations based on on-site measurements of either fuel consumed, activities performed, or materials used throughout the process. The main unit of measurement for both research is Kg of CO2/m2/year, representing the total CO2 emitted by a construction site per year, to be reduced to conform to international environmental sustainability standards.

More than 94% of the total CO_2 emissions from during construction are caused by secondary emissions not considered in LCA,, resulting from the generation of purchased energy and the production of construction materials (Huang et al., 2018). Direct carbon emissions from actual construction operations are found to be much lower (Onat et al., 2020), but this is due to the lack of research assessing the actual emission based on activities performed. The main reason behind this is the challenges that must be faced when gathering data from the construction site, mainly due to workers' willingness to cooperate and limited resources.

A large quota of construction emissions comes from material transportation, even more than emissions produced from building and demolition stages (Weigert et al., 2022). Weigert estimated emissions from construction machinery using usage time from on-site records and the assumption of average fuel consumption based on the engine's power. By knowing a machine's type and its average operation time, fuel consumption rate by hour can be estimated. Multiplying it by the operation time returns the fuel consumption amount andassociated CO2eq emissions.

The total mass of the transported goods (material, components, machinery, waste) is multiplied by the transport distance to calculate the transport emissions to and from the construction site. Ton kilometres of materials (km) can be associated with their CO_2 equivalent using coefficients found in the Ecoinvent database (Wernet et al., 2016). According to Lee (2020), fuel used for material transportation or on site, along with any electrical device required, are the mainsources of CO_2eq emissions. They are the main factors to consider when measuring carbon dioxide emissions.

Dong (2023) proposes three different methods to calculate carbon emissions in the building process. First are direct measurements on-site; gathering data of performed activities is expensive and difficult, and many components must be considered during construction. Furthermore, the high technological requirements reduce the scalability of this method. The second method follows the law of conservation of mass: the mass of resources put into a systemor device must equal the total CO_2 mass produced by the system. Fewer resources are required, but data acquisition is highly prone to errors. This method is not applicable in construction as it is difficult to properly quantify all the input resources and output emissions. The third and last method is called the "emission-factor method," which considers activity data and emission factors for each emission source according to the carbon emission inventory list. The product of all activity data and emission factors will then represent the project's total carbon emission estimation value. This method is the most widely used in calculating carbon emissions due to its clarity and precision. Carbon emission factors of building materials and energy sources are publicly available through the open-access IPCC emission factor database (EFDB, 2023).

Practical CO2 tracking technologies

To obtain buildings' embodied emissions during the construction stage, tremendous efforts must be made, as the process is often data intensive. Heavy machinery work is the greatest cause of fuel consumption in construction. Their average diesel consumption varies greatly depending on the use case and activity type. Construction vehicle equipment often spends more than a third of its usage in an idle state (Hassani M., 2020).

Neve et al. (2022) also showed that only a third of construction time is used to advance the project, resulting in delayed in the estimated schedules. These non-value-adding operations require energy and emit unnecessary emissions (Teizer et al., 2022). Engine activities in heavy machineries used in construction produce large amounts of CO_2 However, these values are estimates based on emission factors from engine data that manufacturers provide and thus may not portray the true picture (Teizer et al., 2022). This is mainly because fuel consumption differs according to the activity of the equipment.

Real-time tracking and dynamic analysis of CO_2 emissions is a relatively new and unexplored field: research involvingtAI to develop net-zero solutions represents only 10% of its publications (Elghaish et al., 2024). IoT, ML, Deep learning (DL), and Digital Twin enhance better data collection in traceable environments that can easily be controlled, leading to more informed decision-making processes (Wood, 2021). These technologies are the most significant drivers of Construction 4.0 through ML, artificial intelligence (AI) algorithms provide valuable insights to make informed decisions (Arsiwala et al., 2023). When considering the whole construction site, actual emissions started rising in the evening and peaked at midnight, after which a steady decline was regularly registered until the afternoon. Most of these emissions are not directly caused by the actual construction but rather by using temporary facilities and collateral activities.

Some considerations need to be taken when using IoT sensors due to their costs and challenges to those collecting the data (research) and those using the machines (workers): installation and removal need to be accommodated by workers schedule and have a financial cost, which also apply to the access to the data collected.

Despite this, the benefits of using IoT sensors have already been shown in literature and far outweigh the costs if experts handle the information produced. Pereira (2021) developed an IoT sensor system for real-time field data monitoring and reporting. ML algorithms will use this data to predict construction truck fuel consumption. The models were trained using sensor data and on-site evidence data to provide accurate estimations of the fuel consumed. The author suggested that a future application would be a web interface and an Application Programming Interface (API) that allows users to input a given route and vehicle data, carry the load, and retrieve fuel consumption estimations to assess the project cost based on the actual scenario in real-time.

IoT sensors, ML and Digital Twin enhance the environmental sustainability of energy systems and help the transition to a net-zero transition (Jia et al., 2024). They consolidatedata collection and and help reducing emissions through insights that help make informed decisions (Zhang et al., 2023). Besides, they have been recognised as an enabling technology (Kourgizou et al., 2021) and a useful tool for the efficiency and rationalisation of energy consumption through real-time monitoring (Hu et al., 2022). They are cost-effective and easily scalable (Gao et al., 2020). BIM or other kinds of simulations support evaluations of energy conservation potential. (Utkucu et al., 2020). ML and DL algorithms, along with IoT sensors (Liang et al., 2023), can also be used for the same purpose (Olu-Ajayi et al., 2022, Desislavov et al., 2023;). Digital twins can also monitor and control emissions (Tahmasebinia et al., 2023). The only aspects not captured by any of these systems are changes in the work environment resulting from project delays or changes in the production system.

Advancements in CO2 tracking commercial solutions

Currently, several software solutions are available on the market for companies to monitor their carbon emissions. Many of these solutions consist of carbon accounting or reporting systems, where users upload their records of activity and energy sources registered by the company or third partie. Most solutions only calculate them based on historical data, providing a general assessment of consumption trends based on past activities as output. Hence, their provided insights do not account for the current condition of the project and any new interventions implemented. These kinds of systems enable the calculation of relevant Key Performance Indicators (KPIs) for carbon emission data in construction projects (Gilani et al., 2020).

Of all the solutions available on the market, three software programs were specifically designed for carbon emission monitoring in construction: Net0 (https://net0.com/), Steer (https://www.steerplatform.com/), and Pulsora (https://www.pulsora.com/). Additionally, one solution was identified in the literature, but it has not been released as a commercial product (CeData). This system integrates carbon emission information based on IFC's (International Finance Corporation) standards on environmental and social sustainability discussed in a previous publication on the subject (Wang et al., 2022a).

From the theoretical perspective, Liu et al. (Liu et al., 2020a) proposed a real-time system for monitoring emissions in the construction stage using a cyber-physical system (CPS). This system enables real-time monitoring and control of the physical world via a sensor network. Similarly, an ideal CPS system was proposed again by Liu et al. (Liu et al., 2020b) in a different article for monitoring the manufacturing process of prefabricated elements using IoT sensors. They would use GPS to track vehicles during transportation while other types of sensors would monitor electricity used by tower cranes, elevators, and vehicles on the construction site. Another study in 2024 deployed CPS to observe emissions from a mountain tunnel construction site . The complete CPS presented consisted of four interconnected parts: "Sensing, Connecting, Computing, and Control." (Yang et al., 2024). These parts collaborate to achieve the system's goals: sensor data is collected and sent to a data storage. After computing it and performing proper analysis, the output is used as reference for taking appropriate control actions. Hong et al. (2024) implemented a live and online Discrete Event Simulation on a Digital Twin Platform. This model reveals how environmentally and economically straining the construction operations process can be. Subsequently, a User Interface visualizes the results for the user in a virtual dashboard found on a commercially available browser.

Although a few of them provide simulations of future conditions and possible solutions or ideas to reduce emissions, no system currently exists to monitor and control emissions simultaneously in real-time.

ML applied to CO2 emissions.

Companies that reduce their own emissions will gain an economic advantage by selling their excess permits to their competitors. This creates an incentive for others to imitate them (Wang et al., 2022b; Shi et al., 2022). Increasing energy efficiency is the most effective way to reduce carbon emissions. Machine learning can be used to develop algorithms to predict energy consumption accurately and identify ways to improve it by directintervention. This information can be used to develop strategies for reducing carbon emissions through predictive models to optimise energy use. A recent research (Zhao et al., 2023) proposed a model consisting of a complex deep learning algorithm, implementing both convolutional neural networks (CNN) (İnik Ö., 2023) and the bacterial foraging algorithm (BFA). Combining these two algorithms' main strengths (CNN's pattern recognition and BFA's strong optimisation capability in complex environments), a strong system was developed with promising results, which could be expanded upon by integrating digital twin technology and on-site data to adapt to unexpected changes in the working environment (Zhao et al., 2023).

All the studies presented here prove that implementing ML is difficult due to the need for data architectures able to process real-time data collected inthe construction site. Still, its contribution will prove to be fundamental for analysing and tracking CO2 emissions.

Findings and Discussion

Analysing the selected literature highlights several key findings related to CO_2 monitoring technologies in construction. First, the study confirms that while the European Union has implemented regulations promoting carbon neutrality by 2050, the construction industry faces significant challenges in meeting these targets. These include the lack of standardised real-time emissions monitoring systems and limited integration of advanced digital tools such as IoT sensors and BIM (van der Heijden, 2023). Furthermore, despite the availability of LCA methodologies, their application is hindered by limitations in accurately measuring real-time emissions during construction operations.

The findings suggest that adopting IoT sensors and ML presents a promising avenue for overcoming current limitations. Real-time tracking systems supported by IoT have demonstrated the potential to significantly enhance data accuracy and transparency (Ahmed et al., 2023; Ghansah et al., 2023). These systems enable the dynamic analysis of CO_2 emissions, allowing stakeholders to monitor construction machinery efficiency and optimise processes in real-time. However, the implementation of such technologies remains restricted due to high costs, technological complexities, and limited user adoption.

ML models also show strong potential to forecast emissions and recommend actionable strategies to reduce energy consumption. For example, hybrid DL algorithms that combine pattern recognition with optimisation capabilities have demonstrated significant promise in dynamic environments. Such systems could be further strengthened by integrating them into digital twin platforms, enabling real-time monitoring and adaptive decision-making during construction. Despite their effectiveness, these technologies remain largely theoretical or in pilot stages, with limited large-scale implementation due to resource constraints and the absence of robust regulatory frameworks to support widespread adoption.

Another critical finding pertains to emissions from non-value-adding activities and idle machinery time. The literature confirms that a substantial proportion of emissions during construction originates from operations inefficiencies rather than value-adding tasks. This highlights the need for operational efficiency strategies, such as optimising construction schedules and minimising equipment idling through advanced tracking and predictive systems. Furthermore, the emissions associated with material transportation remain a significant contributor yet are often underestimated in traditional assessments. Integrating IoT sensors to track real-time transportation emissions can offer a more comprehensive understanding and enable targeted interventions.

While current carbon accounting systems offer valuable insights, their reliance on historical data limits their utility for making immediate decisions. Developing systems that combine real-time monitoring, forecasting, and actionable insights is critical for bridging this gap. Integrating these systems with regulatory frameworks could incentivise industry players to adopt low-carbon practices in the future.

Constraints of current CO2 tracking systems

According to the expert panel, several constraints and limitations hinder the effective implementation of real-time CO_2 monitoring systems in the construction sector, posing challenges to meeting EU regulations for carbon neutrality (reach net-zero emissions) by 2050. A significant barrier is the high cost of deploying IoT sensors and accessing data through subscription-based platforms, making these technologies inaccessible to smaller companies and projects with limited budgets. This financial constraint limits scalability and the widespread adoption of innovative solutions.

The lack of standardised protocols for integrating data from IoT sensors, BIM, and other digital tools creates further complications. This gap increases the complexity of implementing cohesive monitoring systems, requiring advanced computational resources and technical expertise that many construction firms lack. Additionally, limited research on real-time applications of these technologies reduces the availability of validated methodologies, delaying progress in deploying practical, scalable solutions tailored to industry needs. Besides, there is an inaccuracy in attempts at quantifying emissions: usually, only emission factors and duration of activities are considered the main parameters. Even though the emission factors have been proven to be reliable tools for this purpose, their accuracy heavily influences results (Lai et al., 2023). Furthermore, due to the simplicity of this approach, many assumptions are taken, which may lead to only broad estimations. IoT sensor systems, on the other hand, provide real-time monitoring, allowing users to easily identify the main emission sources and find ways to mitigate them (Tao et al., 2018). Their deployment must consider various factors, including availability, cost efficiency, storage system support and compatibility (Agarwal et al., 2020).

Workforce challenges also impact adoption, as engaging workers and managers to embrace digital tools often requires significant behavioural changes. Without clear financial incentives or strong policy support, it is difficult to secure cooperation, particularly for tasks like data collection and reporting. This lack of engagement reduces the effectiveness of CO_2 monitoring initiatives, further delaying compliance with EU regulations.

Data security and computational limitations present additional hurdles, as managing and processing large volumes of real-time data requires robust systems that are often costly and technically demanding. Finally, the narrow focus on direct emissions during construction neglects significant indirect emissions, such as those from material production and transportation, which are critical for meeting EU carbon neutrality targets. These constraints collectively limit the construction sector's ability to adopt comprehensive CO_2 monitoring systems, making it challenging to align with EU regulations and achieve the necessary reductions in greenhouse gas emissions.

Recommendations

According to the expert panel, implementing IoT sensors in construction is critical to achieving effective real-time CO_2 monitoring. These sensors can capture dynamic data on fuel consumption, equipment operation, and material transportation, enabling better identification of significant emission sources. Combined with proper analysis, this data can reduce construction time and costs by facilitating optimised resource allocation. Real-time insights also help ensure compliance with national and international emissions regulations, aligning projects with the EU Policymakers' climate neutrality goals (Elghaish et al., 2024).

Integrating IoT sensors with BIM models enhances CO_2 monitoring, enabling dynamic activity simulations to support accurate emissions predictions. This approach enhances transparency and allows stakeholders to monitor real-time emissions across all stages of the construction process efficiently.

Using hybrid LCA methods s is recommended to improve the precision of embodied carbon calculationsAdditionally, comparing historical data with on-site progress is necessary to develop accurate forecasts and make well-informed decisions. This can be achieved by creating digital repositories of jobsite data, which provide valuable insights into historical trends and enable simulations for future projects.

ML and optimisation algorithms should be leveraged to analyse real-time data, predict future emissions, and identify operational inefficiencies. According to the expert panel, ML models can prioritise Key Performance Indicators, such as emissions per hour or fuel consumption, and propose actionable strategies to minimise emissions. For instance, they can optimise equipment operation schedules, reduce idle times, and prevent engine overheating, significantly reducing CO_2.

Finally, user-friendly dashboards and visualisation tools should be developed to present emissions data and key metrics in an accessible format for project managers. These tools can facilitate data-driven decision-making, ensuring operational strategies are continuously refined to minimise emissions. Applying these recommendations will accelerate the adoption of Construction 4.0 technologies and significantly advance the construction sector's efforts to meet EU carbon neutrality objectives. Table 1 presents all the main recommendations mentioned in this section.

Table 1: Recommendations for monitoring systems.

Code	Recommendation
RC1	Deploy IoT sensors across construction sites to monitor CO_2 emissions in real time.
RC2	Rely on BIM to model and simulate construction activities, linking sensor data for real-time CO_2 monitoring aided by relational databases (Quinn et. al., 2020; Moretti et al., 2020)
RC3	Adopt hybrid LCA approaches combining bottom-up and top-down methods to ensure precise embodied carbon calculations.
RC4	Incorporate historical and real-time data for accurate predictions and decision-making.
RC5	Develop accessible dashboards to visualise Key Performance Indicators (KPIs), such as emissions per hour, fuel usage, and material transportation CO_2 output.
RC6	Use advanced planning and control techniques to reduce idle time and unnecessary emissions.
RC7	Train ML and simulation models to analyse real-time data and predict future CO_2 emissions trends

Conclusions

There is an urgent need to develop an efficient approach to address integrating multi-source construction carbon emissions data (Lu et al., 2024). Due to their economic and environmental implications, it is essential to start applying Construction 4.0 technologies to CO2 monitoring and control in the foreseeable future as they would provide knowledge valid for both research and project managers. These efforts should be followed by ML or other advanced statistical analysis forms to produce accurate results. On the computational side, it is recommended to utilise ML models to identify and prioritise the Key Performance Indicators influencing CO2 emission levels. The insights derived from these models should be presented accessible to project managers, enabling them to make informed decisions on- site. For example, they can optimise operational strategies such as reducing working hours, conducting continuous intensive operations, or preventing engine overheating to minimise emissions effectively. Another potential involves analysing historical data to identify consumption trends and using these insights to simulate and predict future emissions.

An ideal future expansion of these technologies would involve the development of methods to integrate digital twin technologies with IoT sensors and AI to predict and simulate scenarios based on changes in current conditions using ML using algorithms suited for heterogeneous data integration, like convolutional neural networks (Liu et al., 2018). This kind of system would represent an outstanding contribution to studies involving carbon emission in construction and a future direction worth investigating, given access to the necessary competencies and resources.

Adopting these technologies will likely benefit companies and policymakers by providing a more comprehensive understanding of their contributions to greenhouse gas emissions, transforming how carbon footprints are tracked and managed.

Acknowledgements

This research was funded by the Femern Fyrtårn 2.0 – Femern Lighthouse via grant RFPRO-23-0059.

References

Agarwal, P. & Alam, M., (2020). Investigating IoT Middleware Platforms for Smart Application Development. in *Smart Cities—Opportunities and Challenges* 231–244 (Springer, Singapore, 2020).

Ahmed, S. A., Abouelnaga, L. S. & Brahimi, T. (2023). Mapping the Scientific Landscape of Smart Buildings and Climate Change. in *2023 1st International Conference on Advanced Innovations in Smart Cities* (ICAISC) 1–5.

Arsiwala, A., Elghaish, F. & Zoher, M. (2023). Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. *Energy and Buildings* **284**.

Chen, C., Zhao, Z., Xiao, J. & Tiong, R. (2021). A Conceptual Framework for Estimating Building Embodied Carbon Based on Digital Twin Technology and Life Cycle Assessment. *Sustainability* **13**, 13875.

Chung, I. B. & Caldas, C. H. (2024). A Literature Review of Carbon Emissions Monitoring Practices in Construction Projects. In *Construction Research Congress 2024*, 296–304.

Desislavov, R., Martínez-Plumed, F. & Hernández-Orallo, J. (2023). Trends in AI inference energy consumption: Beyond the performance-vs-parameter laws of deep learning. *Sustainable Computing: Informatics and Systems* **38**.

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renewable and Sustainable Energy Reviews* **79**, 390–413.

Dong, Q. (2023). Research Methods of Carbon Emissions. *Highlights in Science, Engineering and Technology* **40**, 412–417.

EFDB – Emission Factor Database (2023): https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

Elghaish, F., Matarneh S., Hosseini M. R. (2024). Predictive digital twin technologies for achieving net zero carbon emissions: a critical review and future research agenda. *Smart and Sustainable Built Environment ahead-of-print*.

European Commission (2015): Energy Performance of Buildings Directive (EPBD) – Compliance study – Final report, Publications Office.

European Commission (2021): European Green Deal – *Research & innovation call*, Publications Office (2021).

Gao, R., Pishdad-Bozorgi, P., Shelden, D. & Tang, S. (2020). Internet of Things Enabled Data Acquisition Framework for Smart Building Applications. *Journal of Construction Engineering and Management* **147**

Ghansah, F. A. & Lu, W. (2023). Major opportunities of digital twins for smart buildings: a scientometric and content analysis. *Smart and Sustainable Built Environment* **13**, 63–84.

Gilani, S., Quinn, C. & McArthur, J. J., (2020). A review of ontologies within the domain of smart and ongoing commissioning. *Building and Environment* **182**, 107099.

Hassani, M., (2020). construction equipment fuel consumption during idling: characterization using multivariate data analysis at Volvo Ce.

Haddaway, Neal R., Biljana Macura, Paul Whaley, and Andrew S. Pullin (2018). ROSES RepOrting Standards for Systematic Evidence Syntheses. *Environmental Evidence* **7,** no. 1, vol. 7.

Hong, J., Shen, G. Q., Feng, Y., Lau, W. S. & Mao, C. (2015). Greenhouse gas emissions during the construction phase of a building: a case study in China. *Journal of Cleaner Production* **103**, 249–259.

Hong, K., Apostolidis, A. & Teizer, J. (2024). Discrete Event Simulation to Predict Construction Equipment Emissions on a Digital Twin Platform. in *41st International Symposium on Automation and Robotics in Construction,* 267-274.

Hu, H., Sun, F., Guo, W. & Pan, L., (2022). Net-Zero Intelligent Energy System: Road to a Successful Carbon Neutral Future. in *2022 12th International Conference on Power, Energy and Electrical Engineering (CPEEE)* 285–291.

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y. & Zhang X. (2018). Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews* **81**, 1906–1916.

İnik, Ö., (2023). CNN hyper-parameter optimization for environmental sound classification. *Applied Acoustics* **202**.

IPCC (2022): Climate Change 2022: Mitigation of Climate Change. *Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

Jia, Y., Wang J., Mao C. (2024). Temporal graph attention network for building thermal load prediction. *Energy and Buildings* **321**, 113507.

Kourgiozou, V., Commin, A., Dowson, M., Rovas, D. & Mumovic, D. (2021). Scalable pathways to net zero carbon in the UK higher education sector: A systematic review of smart energy systems in university campuses. *Renewable and Sustainable Energy Reviews* **147.**

Lai, K. E., Rahiman N. A., Othman N., Moayedi F., Ali K. N., Lim Y. W. (2023). Quantification process of carbon emissions in the construction industry. *Energy and Buildings* **289**.

Lee, Y.-C., Shariatfar, M., Rashidi, A. & Lee, H. W. (2020). Evidence-driven sound detection for prenotification and identification of construction safety hazards and accidents. *Automation in Construction* **113**.

Li, T., Zhao, Y., Zhang, C., Zhou, K. & Zhang, X. (2022). A semantic model-based fault detection approach for building energy systems. *Building and Environment* **207.**

Liang, X., Chen K., Chen S. (2023). IoT-based intelligent energy management system for optimal planning of HVAC devices in net-zero emissions PV-battery building considering demand compliance. *Energy Conversion and Management* **292**.

Liu, S., Li, M., Zhang, Z., Xiao, B. & Cao, X. (2018). Multimodal Ground-Based Cloud Classification Using Joint Fusion Convolutional Neural Network. *Remote Sensing* **10** (6).

Liu, G., Fu Y., Hong J., Li R., Yang H., Mao C. (2020a). Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction. *Journal of Cleaner Production* **246**.

Liu, G., Chen R., Xu P., Fu Y., Mao C., Hong J., (2020b). Real-time carbon emission monitoring in prefabricated construction. *Automation in Construction* **110.**

Lu, Y., Song, G., Li, P. & Wang, N., (2024). Development of an ontology for construction carbon emission tracking and evaluation. *Journal of Cleaner Production* **443**,

Moretti, N., Xie, X., Merino, J., Brazauskas, J. & Parlikad, A. K. (2020). An open BIM Approach to IoT Integration with Incomplete As-Built Data. *Applied Sciences* **10.**

Neve, H., Wandahl, S., Lindhard, S., Teizer, J. & Lerche, J. (2022). Learning to see value-adding and non-value-adding work time in renovation production systems. *Production Planning & Control* **33**, 790–802.

Olu-Ajayi, R., Alaka, H., Sulaimon, I., Sunmola, F. & Ajayi, S. (2022). Building energy consumption prediction for residential buildings using deep learning and other machine learning techniques. *Journal of Building Engineering* **45**,

Onat, N. C. & Kucukvar, M. (2020). Carbon footprint of construction industry: A global review and supply chain analysis. *Renewable and Sustainable Energy Reviews* **124**.

Pereira, G. (2021). Fuel Consumption Prediction for Construction Trucks: A Noninvasive Approach Using Dedicated Sensors and Machine Learning. *Infrastructures* **6.**

Quinn, C., Shabestari A. Z., Misic T., Gilani S., Litou M. & McArthur J. J. (2020). Building automation system - BIM integration using a linked data structure. *Automation in Construction* **118.**

Shi, B., Li, N., Gao, Q. & Li, G. (2022). Market incentives, carbon quota allocation and carbon emission reduction: Evidence from China's carbon trading pilot policy. *Journal of Environmental Management* **319.**

Tahmasebinia, F., Lin, L., Wu, S., Kang, Y. & Sepasgozar, S. (2023). Exploring the Benefits and Limitations of Digital Twin Technology Building Energy. *Applied Sciences* **13**.

Tao, X., Mao, C., Xie, F., Liu, G. & Xu, P. (2018). Greenhouse gas emission monitoring system for manufacturing prefabricated components. *Automation in Construction* **93**, 361–374.

Teizer, J. & Wandahl, S. (2022). Simplified Emissions Measurement System for Construction Equipment. In *Construction Research Congress 2022*.

Utkucu, D. & Sözer, H. (2020). Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort. *Automation in Construction* **116.**

Van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. *Building and Environment* **244.**

Wang, Y., Wangari, V. W., Yang, D., Shao, S. & Qin, X., (2022a). A systematic literature review on research and progress of road traffic soundscape. *in International Conference on Smart Transportation and City Engineering* **12460,** 276–286.

Wang, K.-H., Liu, L., Zhong, Y. & Lobonţ, O.-R. (2022b). Economic policy uncertainty and carbon emission trading market: A China's perspective. *Energy Economics* **115**.

Weigert, M., Melnyk, O., Winkler, L. & Raab, J. (2022). Carbon Emissions of Construction Processes on Urban Construction Sites. *Sustainability* **14**.

Wernet G., Bauer C., Steubing B., Reinhard J., Moreno-Ruiz E. & Weidema B. (2016). The ecoinvent database version 3. *The International Journal of Life Cycle Assessment*, **21** (9), 1218-1230.

Wood, L. (2021). The role of digitalisation in achieving net zero. *Costain*, available at https://www.costain.com/news/insights/the-role-of-digitalisation-in-achieving-net-zero/

Yang, J. Li J., Liu Z., Liu Y., Li Z. (2024). Real-Time Monitoring Technology for Carbon Emissions in Mountain Expressway Tunnel Construction. *E3S Web Conf.* **573**.

Zhang, X. & Zhang, X. (2020). A subproject-based quota approach for life cycle carbon assessment at the building design and construction stage in China. *Building and Environment* **185**.

Zhang, H. & Sun, R. (2023). A novel optimal management method for smart grids incorporating cloud-fog layer and honeybee mating optimization algorithm. *Solar Energy* **262**.

Zhao, Y., Liu, L., Wang, A. & Liu, M. (2023). A novel deep learning based forecasting model for carbon emissions trading: A comparative analysis of regional markets. *Solar Energy* **262.**