Decision Making: Applications in Management and Engineering

Journal homepage: www.dmame-journal.org
ISSN: 2560-6018, eISSN: 2620-0104

Digital Twin-Enhanced MCDM Framework for Circular Construction Dynamic Lifecycle Optimization of Hybrid Concrete Mix Design

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ARTICLE INFO

Article history:
Received 25 January 2025
Received in revised form 10 June 2025
Accepted 7 July 2025
Available online 10 August 2025

Keywords:
Hybrid Concrete Mix Design, Circular Construction, Digital Twin, Multi-Criteria Decision-Making (MCDM), Particle Swarm Optimization (PSO).

ABSTRACT

This study introduces an integrated, intelligent framework aimed at optimising hybrid concrete mix design by employing Digital Twin (DT) modelling, dynamic decision-making processes, and real-time optimisation. The DT model is developed to continuously mirror and update the changing physical characteristics of hybrid concrete materials, thereby facilitating predictive simulations and lifecycle assessments. Data quality is ensured through pre-processing and feature extraction procedures, which involve cleaning, normalisation, and parameter selection focused on compressive strength, recyclability, embodied carbon, and degradation indicators. A retained carbon emission accounting model is utilised to dynamically monitor environmental impacts throughout the construction lifecycle, thereby enabling the formulation of low-carbon mix design strategies. The framework incorporates recycled aggregates, biochar, and industrial waste materials, aligning with sustainability objectives and circular economy principles. A dynamic multi-criteria decision-making (MCDM) process, based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), is employed to assess mix design alternatives. This process evaluates various criteria including cost factors, performance indicators, and environmental impacts, with adaptable weight adjustment mechanisms tailored to the specific phase of the project. Optimisation of mix designs is conducted using PSO, which dynamically integrates data derived from MCDM procedures and Decision Tables (DT). A real-time feedback and decision-making interface allows operators to actively oversee operations, enabling proactive adjustments and informed decisions. The integration of these components results in an adaptive and resilient system for sustainable hybrid concrete construction, balancing structural performance with environmentally conscious practices. Future investigations may expand the framework by incorporating AI-based predictive maintenance and adaptive learning algorithms for real-time modelling of material behaviour. Furthermore, extending the system's scalability to accommodate large-scale infrastructure projects may enhance its applicability within smart construction environments.

1. Introduction

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https://doi.org/10.31181/dmame8220251476

The rise of sustainable construction practices has intensified interest in circular construction, prompting substantial advancements in this domain. Circular construction embodies a resource-efficient and lifecycle-oriented approach that seeks to replace the conventional linear model of 'take-make-dispose' with one focused on reducing waste, reusing materials, and recycling resources to support sustainability and mitigate environmental impact [22]. A significant aspect of lowering the environmental footprint in infrastructure projects lies in the utilisation of hybrid concrete mixes, which incorporate alternative binders and recycled aggregates alongside low-carbon constituents [31].

Designing hybrid mixes necessitates navigating numerous intricate calculations, as it requires a strategic balance between mechanical performance, durability, economic viability, and environmental considerations. Traditional material selection methodologies encounter limitations in dynamically evolving contexts due to their reliance on static variables and oversimplified models. These methods often neglect to capture real-time changes or the multifaceted interdependencies among environmental, economic, and social factors [13]. Consequently, they are inadequate in adapting to fluctuations in resource availability, shifting regulatory frameworks, or evolving performance standards. Moreover, conventional approaches frequently lack the flexibility to accommodate new materials or incorporate long-term sustainability elements such as energy efficiency and recyclability, resulting in suboptimal outcomes within complex and changing environments.

A promising alternative for dynamic hybrid concrete mix design has emerged through the integration of DT technology and MCDM frameworks. These data-driven methods offer real-time strategies that consistently align material innovation with circular economy objectives [4]. Online simulations enable the creation of DTs by replicating the operational behaviours of physical assets, thus producing accurate virtual counterparts [18]. DT platforms enhance the monitoring of materials and systems in construction, thereby improving lifecycle management capabilities [12]. These platforms support informed decision-making by allowing users to evaluate environmental and load condition variations in real time when selecting hybrid concrete mix materials [34]. Furthermore, DTs provide predictive insights into material degradation timelines and simultaneously assess exposure to environmental stressors, thereby contributing to the development of more resilient infrastructure [16]. When integrated with MCDM systems, DTs empower stakeholders to manage conflicting objectives, such as improving material strength while reducing carbon emissions [25]. This integration allows for the selection of materials based on both project-specific needs and regulatory constraints. In early project phases, collaborative decision-making concerning material selection is facilitated through the combined utility of Decision Technologies and Multiple Criteria Decision Analysis, ensuring optimal choices while maintaining adaptability to changes in project information.

Authentic circular construction systems are shaped by three sequential design phases, which guide materials through defined pathways from inception to end-of-life [23]. The proposed DT-enhanced MCDM framework supports the optimisation of hybrid concrete mix performance throughout the entire lifecycle of circular infrastructure development. It enables ongoing evaluation of circular economy materials by integrating real-time data with predictive analytics and lifecycle assessment methodologies. This decision-making process standardises hybrid concrete mix design according to project-specific sustainability criteria, including assessments of carbon emissions, energy consumption, mechanical performance, cost considerations, and recyclability. The framework is embedded with responsive feedback mechanisms that automatically react to unforeseen developments such as material shortages, equipment failures, or newly imposed regulations. The study addresses key limitations in material optimisation under lifecycle analysis, advancing the digital transformation of sustainability in construction.

Through comprehensive testing and real-world implementation, this framework demonstrates its effectiveness in producing adaptive hybrid concrete mixes that yield environmental advantages, enhanced strength, and cost efficiency. By combining DTs with MCDM approaches in hybrid concrete design, the construction industry is equipped to develop infrastructure that is more intelligent, sustainable, and resilient. DTs offer real-time performance insights, enabling material use to be optimised, while MCDM methodologies assist in balancing sustainability objectives, cost management, and structural requirements across all phases of construction. This integration supports the creation of efficient, environmentally responsible, and long-lasting construction solutions.

2. Related Works

In recent years, increasing emphasis has been placed on the utilisation of advanced computational methodologies for the design and optimisation of hybrid concrete mixes within the framework of circular construction. Researchers have explored various approaches to address the multifaceted challenges associated with material selection and lifecycle optimisation, ranging from experimental procedures to digital simulations and decision support systems.

Summary of Key Studies in Field: Table 1 presents a synthesis of significant studies in this domain, outlining the researchers involved, the methodologies adopted, and a comparative analysis of their respective strengths and limitations. These studies indicate a diverse array of optimisation strategies for hybrid concrete, encompassing conventional MCDM techniques, machine learning-based models, and Digital Twin technologies. Each method contributes distinct perspectives and solutions relevant to enhancing system performance within a circular economy context.

This literature review provides a critical examination of the advantages and drawbacks inherent in these methodologies, thereby offering a comprehensive overview of prevailing research trends. In doing so, it identifies existing gaps that are addressed by the proposed framework, which integrates Digital Twin technology with MCDM to advance the optimisation of hybrid concrete design.

Table 1
Summary of Recent Studies on Digital Twin Integration in Sustainable Construction

Author(s)	Techniques Involved	Advantages	Disadvantages
Weerapura et al. [32]	Digital Twin, Risk Management, Predictive Analytics	Real-Time Risk Monitoring, Improves Efficiency	High Cost, Continuous Data Required
Mirwais et al. [21]	AI-Driven Design, 3D Concrete Printing	Optimizes Material Use, Reduces Waste	High Computational Cost, Limited to 3D Printing
Mêda et al. [19]	Incremental Digital Twin, Circular Construction	Supports Data-Driven Decision-Making, Promotes Circular Economy	Complexity in Conceptualization, Integration Challenges
Petri et al. [26]	Digital Twin, Performance Management Framework, Data Integration	Enhances Operational Insight, Enables Proactive Maintenance	Data Standardization Issues, High Initial Implementation Effort
Jiang et al. [15]	Digital Twin, Construction 4.0	Enhances Coordination, Improves Management	High Tech Infrastructure, Resistance from Industry

Weerapura et al. [32] present a framework integrating DT technology with Risk Management and Predictive Analytics to enhance operational efficiency and risk mitigation within ready-mix concrete production. Their methodology utilises continuous real-time monitoring to oversee operational risks, thereby optimising manufacturing processes. A key benefit of this approach is its capacity to anticipate and minimise potential risks through persistent data surveillance, which strengthens the decision-making framework. Nonetheless, the approach entails substantial initial capital expenditure and demands ongoing data entry, which may challenge system performance and data management infrastructures. The investigation by Mirwais et al. [21] explores the utilisation of Artificial Intelligence

(AI)-powered design in combination with 3D Concrete Printing to maximise design flexibility and construction accuracy for sophisticated concrete structures. The AI-automated designs demonstrate superior material efficiency, significantly reducing waste across the components of printed structures. These reductions contribute favourably to environmental sustainability objectives. However, the necessity for advanced computational resources restricts the deployment of this technique within conventional construction practices, despite its efficacy in 3D printing applications.

Mêda et al. [19] propose a DT-based framework employing incremental modelling techniques to advance circular construction via enhanced data-driven decision systems. By deploying DTs at multiple construction stages, the framework enables continuous real-time data acquisition coupled with iterative performance enhancement grounded in feedback loops. This system's principal strength is its alignment with circular economy tenets, optimising resource conservation and utilisation efficiency. However, its implementation requires sophisticated technological tools and expert personnel, posing integration challenges within existing construction workflows. The research of Petri et al. [26] centres on optimising building production processes through the integration of DT and AI technologies. The convergence of these systems augments decision-making capabilities and streamlines construction operations. AI applications during production phases improve scheduling accuracy, resource allocation, and cost control, thereby elevating overall operational effectiveness. While the method yields significant benefits in decision quality and project management, its widespread adoption is impeded by high costs and the technical complexities of system integration.

Jiang et al. [15] investigate the application of DT in facilitating Construction 4.0, aiming to enhance project supervision and coordination. This approach improves operational control by synchronising real-time data from diverse network sources, fostering enhanced cross-phase collaboration, reduced project timelines, and superior quality outcomes. Nevertheless, the broad implementation of this technology is constrained by resistance within traditional construction methodologies and the necessity for advanced information technology infrastructures. Despite the promising advancements of AI, DT, and allied digital technologies, their practical applications remain limited, frequently confined to specialised contexts such as 3D printing due to intensive manual data requirements and computational demands. The integration of DT frameworks into traditional construction is hindered by infrastructural limitations and industry resistance, while substantial implementation costs further restrict widespread deployment. Consequently, the potential of these technologies to optimise lifecycle management and decision-making remains underexploited.

The proposed DT-enhanced MCDM framework offers a versatile and cost-efficient solution to these challenges. This integrated model addresses critical shortcomings including reliance on static decision data, elevated lifecycle expenses caused by insufficient predictive planning, inadequate incorporation of sustainability metrics, restricted responsiveness to dynamic project changes, and difficulties in applying circular economy principles. By facilitating dynamic decision-making supported by lifecycle predictive analytics and real-time data integration, the framework optimises resource allocation across all phases of construction projects. Furthermore, it surmounts existing integration and scalability barriers prevalent in current digital construction methodologies, delivering an adaptable and sustainable operational paradigm.

3. Proposed System Model

Supported by environmental monitoring capabilities, this novel concrete mix approach facilitates material modifications that maintain environmental integrity throughout the various stages of construction. This framework constitutes the principal element sustaining the current carbon emission accounting model, which estimates emissions from initial material sourcing through construction activities to final demolition. The DT system continuously gathers real-time data to refine and optimise the model, enabling ongoing evaluation of the environmental impact associated with each mix design choice. By integrating this system, engineers and project managers gain access to updated carbon performance metrics [16], guiding informed decisions towards more sustainable material selections. The methodology employs the TOPSIS to concurrently assess environmental criteria, economic factors, mechanical performance, and durability attributes. This dynamic carbon monitoring mechanism is embedded within the design procedures to ensure sustainability is upheld throughout the entire project lifecycle, from inception to completion. Figure 1 illustrates the comprehensive model structure diagram.

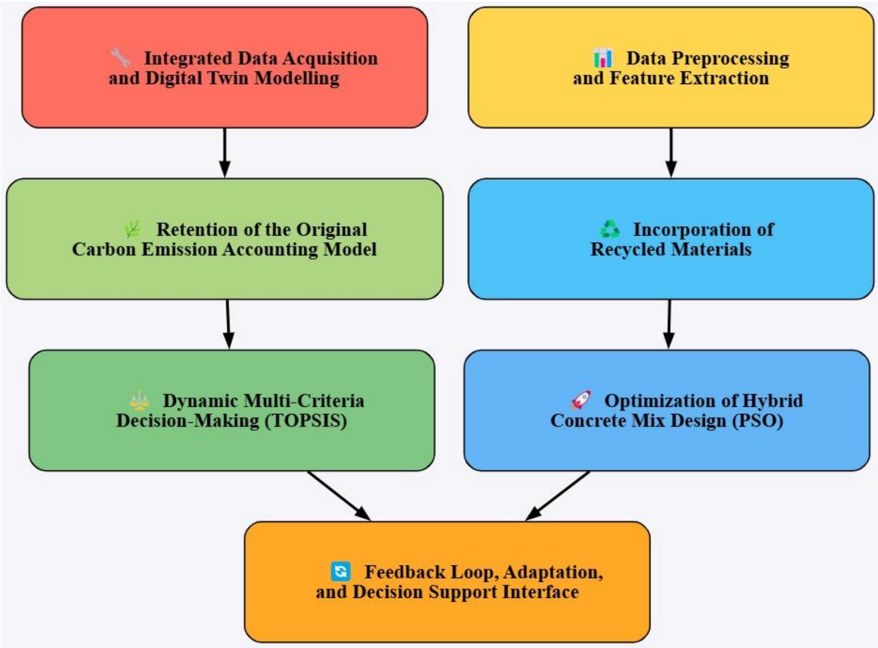

Fig.1. Block Diagram of the Proposed Model

The methodology specifies the utilisation of hybrid concrete mixes that incorporate recycled materials to support both resource conservation and circular construction principles. A thorough analysis of varying substitution rates among recycled aggregates, biochar, and industrial by-products such as fly ash and slag is essential, conducted through simulation and evaluative processes. Recycled aggregates sourced from construction and demolition waste systems contribute to the preservation of natural resources by enabling material reuse, while biochar functions dually as a strength-enhancing additive and an effective carbon capture agent. Industrial waste materials act as partial replacements for cement, thereby reducing overall energy consumption and mitigating environmental impacts. Modelling these material substitutions facilitates the assessment of sustainability outcomes alongside performance evaluations, ensuring that each concrete mix satisfies sustainability criteria without compromising structural integrity. The framework integrates PSO algorithms to embed recycled content strategies within the design process, optimising workflows to produce concrete mixes that align with sustainability objectives and construction standards whilst maintaining superior performance levels.

3.1 Integrated Data Acquisition and Digital Twin Modelling

The proposed framework is founded on the integrated process of acquiring high-fidelity data and constructing intelligent DT models. It continuously gathers real-time information from embedded sensors coupled with Internet of Things (IoT) devices deployed at the construction site [29]. These devices monitor key parameters, including ambient temperature, humidity, curing kinetics, hybrid concrete stress-strain behaviour, and environmental testing conditions [5]. Concurrently, historical project data—comprising completed construction records, material documentation, sustainability reports, and lifecycle cost information—are also collected [1]. The combination of real-time site data acquisition and historical dataset compilation produces a comprehensive, multidimensional repository that reflects current conditions and ongoing material responses [8]. The DT for hybrid concrete materials is developed through analysis of this aggregated data, yielding a high-precision virtual model of the material and its evolving construction environment. Incoming sensor data initiates continuous updates to the DT, enabling real-time tracking of changes in material properties and site conditions [27]. Predictive analytics and virtual simulations allow the DT to replicate current states and forecast future performance across diverse operational scenarios. Serving as the foundational technology for lifecycle assessment, decision-making, and ongoing optimisation, the DT underpins adaptive, intelligent circular construction practices [10].

Real-time monitoring integrated with predictive analytics and adaptive decision-making based on the DT model enhances material efficiency and sustainability throughout construction lifecycles. The fusion of high-fidelity IoT sensor data and historical records sustains the DT's current understanding of hybrid concrete materials and site parameters. A dynamic feedback mechanism identifies material inefficiencies proactively, enabling adjustments that optimise resource allocation, reduce waste, and promote material reuse and recycling. Scenario simulations generated by the DT facilitate predictions of material performance under varying environmental conditions, informing decisions that extend material service life and structural durability. The DT systematically supports fundamental circular construction principles by minimising environmental impact, maximising resource utilisation, and fostering system resilience.

3.2 Data Pre-Processing and Feature Extraction

The subsequent critical stage following data acquisition involves comprehensive data pre-processing and feature extraction to ensure dependable information utilisation. The precision of downstream analyses is heavily influenced by the inconsistencies present in raw data collected from sensors and historical archives, which often contain noise, outliers, and missing or unreliable entries. Therefore, rigorous data cleaning protocols are essential to eliminate erroneous readings, rectify inconsistencies systematically, and appropriately address absent or incomplete data points. Normalisation procedures are then applied to standardise parameter scales, enabling comparability among diverse measurements despite differences in units and ranges [24]. Upon completion of cleaning and standardisation, key features pertinent to hybrid concrete mix design and lifecycle performance are identified through feature extraction methods [2]. These include compressive strength, workability (such as flow and placement ease), embodied carbon dioxide footprint, recyclability index, as well as lifecycle assessment and degradation indicators, all systematically derived from the dataset. The MCDM models and optimisation algorithms depend on these extracted features as essential input variables. The comprehensive nature of the data, combined with feature extraction techniques, enhances the data's intrinsic value, thereby improving the accuracy and operational resilience of the decision-making framework [17].

3.3 Retention of the Original Carbon Emission Accounting Model

The current framework preserves the foundational carbon emission calculation model as its central element for hybrid concrete mix design. This model quantifies carbon footprints across all phases, encompassing material sourcing, transportation, construction, operation, and eventual demolition. Within this framework, the data layer facilitates continuous monitoring and optimisation of the environmental impact associated with hybrid concrete mix designs throughout the entire construction lifecycle. The Digital Twin system ingests real-time data inputs to enable ongoing updates of the carbon footprint, allowing stakeholders to assess the emissions implications of various mix alternatives. This capability supports decision-makers in selecting low-carbon materials while balancing other critical criteria such as cost efficiency and structural durability. By continuously adapting, the model embeds sustainability at every stage of the design process, thereby advancing circular construction practices that effectively mitigate carbon emissions.

3.4 Incorporation of Recycled Materials

The hybrid concrete mix design framework substantially benefits from the integration of recycled materials, addressing environmental concerns through the prudent and sustainable utilisation of resources. This system allows practitioners to explore the combined influence of recycled aggregates, biochar, and industrial waste products on both structural performance and ecological impact by experimenting with varying proportions of substitution. The use of aggregates derived from construction and demolition waste mitigates the depletion of natural resources by promoting the reuse of existing materials. Biochar, generated through an advanced biomass carbonisation process, not only enhances the durability of concrete but also acts as a carbon sink, thereby contributing to environmental protection. Moreover, incorporating fly ash and industrial slag as partial cement substitutes significantly reduces both the energy demand and carbon emissions associated with concrete production. By embedding these components into the mix design, the model facilitates comprehensive evaluations of mechanical behaviour and sustainability outcomes across multiple material combinations, guiding the identification of optimal formulations that balance longevity and ecological responsibility. The application of circular economy principles thus yields superior sustainability advantages while simultaneously improving concrete quality through effective waste material reclamation.

3.5 Dynamic Multi-Criteria Decision-Making (MCDM) Process Using TOPSIS

Once a clean and well-structured dataset is established, the subsequent phase involves implementing a dynamic MCDM approach, such as the TOPSIS [3]. TOPSIS is particularly suited for handling multiple, sometimes contradictory criteria, and is favoured due to its capability to generate distinct, rank-ordered outcomes. During this stage, each candidate hybrid concrete mix design is assessed against key criteria including cost-effectiveness, mechanical strength, carbon footprint, recyclability, durability, and lifecycle performance. The fundamental concept underpinning TOPSIS is that the optimal alternative should be positioned as closely as possible to the Positive Ideal Solution (PIS) and as far as possible from the Negative Ideal Solution (NIS). The PIS denotes a hypothetical option exhibiting the most favourable values across all evaluated criteria—such as lowest cost, highest durability, and minimal environmental impact—whereas the NIS represents the least favourable values for the same criteria. The TOPSIS method involves normalising the decision matrix, assigning appropriate weights to each criterion, and computing the geometric distances of each alternative from both the PIS and NIS. The alternatives are then ranked according to their relative closeness to the PIS, ensuring a balanced evaluation that accounts for both performance and compromises among multiple, often conflicting factors. This makes TOPSIS particularly effective for complex decision-making scenarios in construction and sustainability assessments. The formula used to calculate the relative closeness C_I of the alternative i to the ideal solution is mathematically:

$$C_I = \frac{s_I^-}{s_I^+ + s_I^-} \qquad (1)$$

In this context, s_I^+ denotes the Euclidean distance of alternative I from the positive ideal solution and s_I^- represents the Euclidean distance of alternative from the negative ideal solution.

The TOPSIS framework is modified to include a dynamic weighting system, enabling the relative significance of evaluation criteria to vary throughout different lifecycle stages [14]. For example, during the initial construction phase, mechanical strength and workability receive greater emphasis, while in subsequent phases, focus shifts towards sustainability and recyclability. This adaptable weighting strategy ensures the selection of a hybrid concrete mix that is optimised for immediate performance while also remaining sustainable, cost-effective, and viable across the entire lifespan of the construction project [20]. In summary, applying TOPSIS within a dynamic MCDM framework offers a transparent, flexible, and methodologically sound approach to decision-making.

3.6 Optimization of Hybrid Concrete Mix Design Using Particle Swarm Optimization (PSO)

PSO techniques are employed following initial decision-making to refine hybrid concrete mix designs, ultimately enhancing lifecycle performance. PSO functions as an optimisation algorithm that identifies the optimal combination of mix parameters while adhering to the constraints of circular construction [28]. Drawing inspiration from the collective behaviour observed in bird flocks and fish schools, PSO utilises a population of candidate solutions, referred to as particles, which collaboratively explore the solution space. The position xi and velocity vi for each particle i get updated through these standard PSO equations during an iteration:

$$V_I(T+1) = W.V_I(T) + C_1.R_1.(P_{bestI} - X_I(T)) + C_2.R_2.(G_{bestI} - X_I(T)) \quad (2)$$

$$X_I(T+1) = X_I(T) + V_I(T+1) \quad (3)$$

G_{bestI} is defined as maximum global position obtained by entire swarm, P_{bestI} is maximum position against the global position that obtained by particle itself, R_1 , R_2 are randomly selected numbers from 0 to 1, and W is the inertia weight to govern the non-of previous velocities.

The iterative process of guiding particles towards the most promising areas within the solution space characterises the PSO algorithm. This method is well-suited for optimising multi-objective problems, such as minimising embodied energy, reducing lifecycle costs, enhancing material durability, and increasing recyclability, specifically within the scope of hybrid concrete mix design [30]. By integrating real-time feedback from the Digital Twin alongside the weighted priorities established through the MCDM analysis, the PSO-driven optimisation ensures that the final concrete mix selections satisfy structural performance and economic viability criteria, while simultaneously aligning with sustainability and circular economy principles. Consequently, this intelligent optimisation phase plays a crucial role in fine-tuning and validating the most effective concrete mix configurations, thereby supporting optimal lifecycle performance [27].

3.7 Feedback Loop, Adaptation, and Decision Support Interface

The final stage of the framework involves incorporating a real-time feedback loop alongside a dynamic decision support interface, facilitating ongoing adaptability and informed decision-making throughout the construction lifecycle [6]. The Digital Twin model is continuously updated with real-time sensor and monitoring data as construction progresses on site. This capability enables the system to manage unforeseen deviations or unexpected behaviours of materials or environmental conditions that were not anticipated during the initial development phase [9]. Upon detecting such variations, the system automatically activates an adaptive mechanism that re-assesses the MCDM scores and re-executes the PSO optimisation with adjusted parameters to maintain optimal lifecycle performance. This real-time recalibration ensures the hybrid concrete mix design remains durable, sustainable, and efficient despite evolving site conditions. The decision support dashboard intuitively presents critical information—including lifecycle projections, material performance forecasts, risk notifications, and updated optimisation recommendations—thereby guiding user decisions [33]. By delivering data to engineers, site managers, and decision-makers in an accessible and actionable format, the system empowers confident and proactive decision-making on site [7]. Ultimately, the construction project functions as a living, adaptive system where the feedback loop and decision support mechanisms significantly enhance flexibility, resilience, and overall project success [11].

4. Performance Evaluation

The evaluation of the hybrid concrete mix design framework is conducted by validating the optimisation accuracy and comparing results through the TOPSIS methodology, which employs a MCDM approach to assess mix designs relative to conventional alternatives. This evaluation considers key performance indicators such as compressive strength, durability, carbon footprint, and lifecycle costs. Concurrently, PSO refines the mix designs to meet established sustainability objectives and performance standards. The integration of real-time data within the Digital Twin enables performance validation by comparing construction measurements, demonstrating that the framework achieves superior sustainability, energy efficiency, and material durability compared to traditional methods. Within the Transportation Simulation component, delivery routes are analysed by considering different vehicle types and distances to reduce carbon emissions through fuel consumption assessment.

Critical parameters influencing emission reductions include optimising routes to minimise travel distance, vehicle fuel efficiency, load capacity, driving speed, and stop frequency. These factors collectively contribute to lower fuel use and enhanced transportation efficiency, thereby reducing carbon emissions. Further environmental benefits are realised by optimising delivery schedules and employing energy-efficient vehicles. Continuous emission reductions are observed as the Digital Twin facilitates real-time monitoring throughout all construction phases. The Circular Economy Analysis examines long-term sustainability effects by tracking multiple cycles of material reuse, focusing on recycled aggregates, biochar, and industrial waste over periods of 10 to 15 years. This analysis investigates material degradation trends while assessing potential reuse scenarios and associated energy consumption. By informing material selection and prolonging durability, the framework reduces reliance on virgin resources, thereby preserving quality throughout the lifecycle of the construction process.

Figure 2 compares the carbon dioxide (CO_2) emissions, expressed in kilograms, associated with three commonly utilised construction materials: concrete, steel, and wood. Concrete exhibits a carbon footprint of approximately 900 kg CO_2, representing a moderate level relative to the other materials. Despite its widespread use owing to its strength, durability, and cost-effectiveness, concrete production is energy-intensive, with cement manufacture being a principal contributor to CO_2 emissions. Steel displays the highest carbon footprint among the three materials, with emissions approaching 2000 kg CO_2. This elevated value reflects the substantial energy demands inherent in steel production, including ore extraction, high-temperature smelting, and long-distance transport. Consequently, steel's carbon intensity poses significant environmental challenges within the construction sector.

In contrast, wood has the lowest carbon footprint, approximately 200 kg CO_2, which is comparatively low relative to most other building materials. This advantage arises partly because wood processing consumes less energy and its growth phase acts as a carbon sink, sequestering CO_2 from the atmosphere. This intrinsic sustainability benefit positions wood as a favourable material within circular construction practices, which emphasise resource efficiency, material recycling, and minimisation of environmental impact. The considerable variation in embodied carbon among these materials underscores the critical importance of strategic material selection in construction projects. As the industry transitions towards more sustainable and circular models, reducing embodied carbon—either through utilising materials such as wood or optimising hybrid concrete mixes that balance performance with environmental criteria—is imperative. Such approaches are essential to decreasing the overall carbon footprint of construction activities and promoting the development of greener, more resilient built environments.

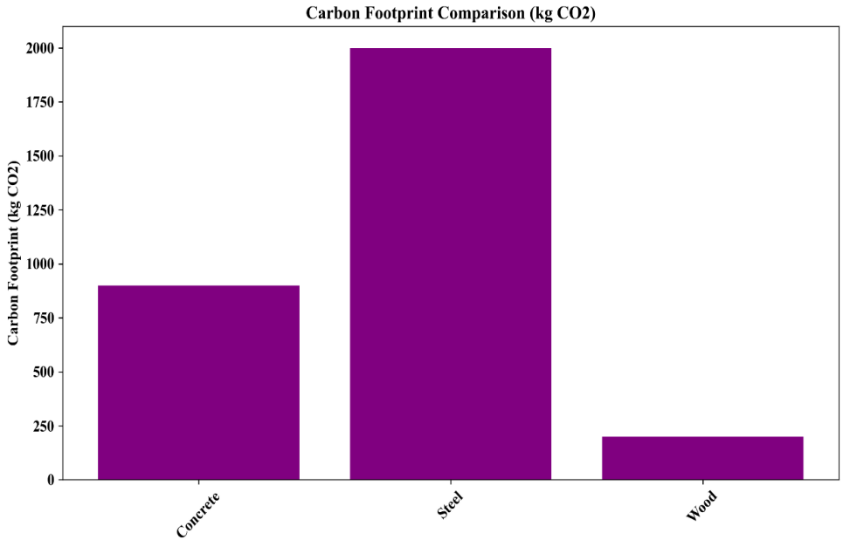

Fig.2. Carbon Footprint

Figure 3 presents a comparison of compressive strength among steel, concrete, and wood. Steel exhibits the highest compressive strength at approximately 250 MPa, significantly exceeding that of both concrete and wood. Concrete demonstrates a compressive strength near 30 MPa, rendering it suitable for applications involving moderate load-bearing requirements typical in conventional construction. In this scenario, wood surpasses concrete, with a compressive strength around 40 MPa, offering a lightweight and renewable option for certain construction purposes. The pronounced disparity in compressive strength highlights steel's superiority in projects demanding exceptional structural performance. Conversely, concrete provides a balanced compromise between cost-efficiency and durability, while wood represents a sustainable choice where extreme strength is not a primary concern. Achieving both structural effectiveness and sustainability objectives necessitates careful material selection based on compressive strength criteria aligned with the specific demands of each project.

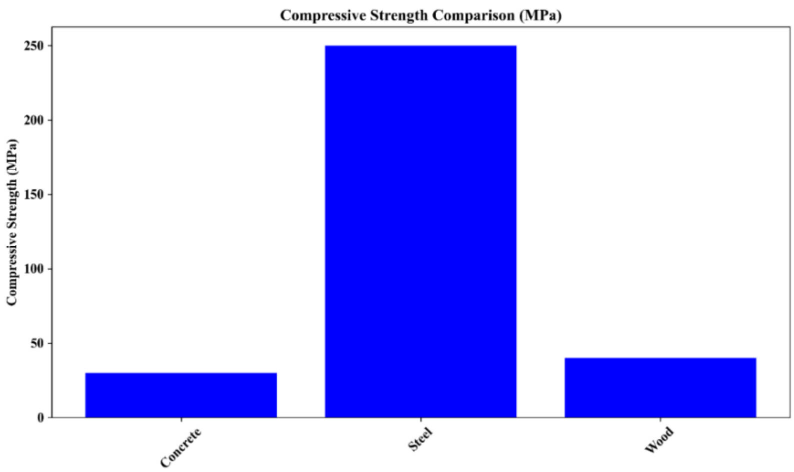

Fig.3. Compressive Strength

Figure 4 illustrates a durability comparison among steel, concrete, and wood. Steel emerges as the most durable material, with an average service life exceeding 100 years, significantly outperforming the other two materials. Concrete follows, offering durability of approximately 50 years, which provides a balanced combination of strength, cost-effectiveness, and lifespan suitable for infrastructure and building applications. Although wood has the shortest service life, around 40 years, it remains a viable option where factors such as sustainability, aesthetic appeal, or ease of handling take precedence over maximum longevity. The considerable variation in durability underscores steel as the preferred choice for projects requiring long-term, high-performance structures. Meanwhile, concrete presents a more economical alternative with adequate durability, and wood is best suited for projects prioritising environmental benefits, design versatility, or other specific material characteristics.

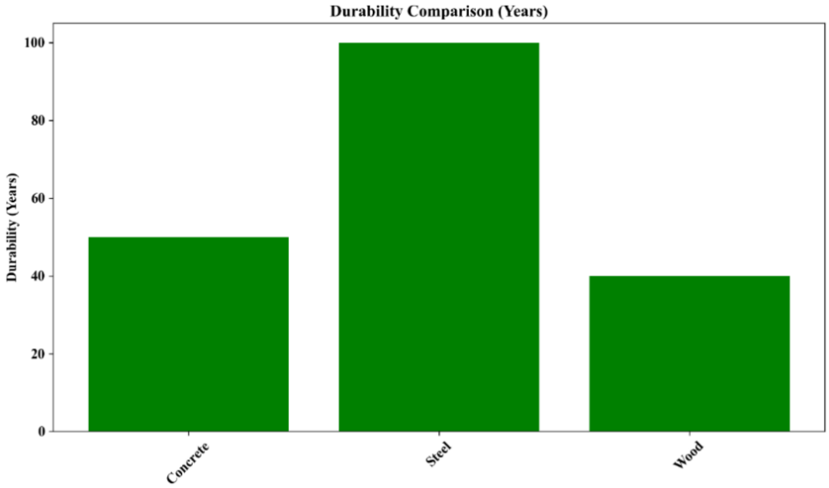

Fig.4. Durability Comparison

As depicted in Figure 5, durability demonstrates an upward trend corresponding with improvements in design, progressing from low durability in Design 1 to moderate in Design 2, and reaching high durability in Design 3. Design 1 exhibits a low median durability accompanied by a wide distribution and several outliers on the lower end, indicating greater variability and reduced consistency. In contrast, Design 2 shows increases in both median and overall durability values relative to Design 1, alongside diminished variability, suggesting enhanced reliability in performance. Design 3 attains the highest median durability with the narrowest distribution, signifying not only superior durability but also more consistent and predictable performance across samples. Overall, the transition from Design 1 to Design 3 reflects substantial advancements in the concrete mix formulation aimed at optimising durability while minimising performance variability.

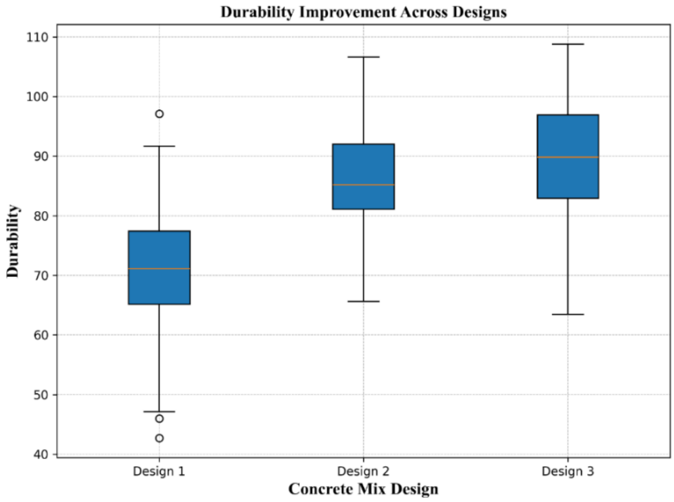

Fig.5. Durability Design

Figure 6 illustrates the trend of diminishing embodied energy across successive optimisation iterations. At the initial iteration, the embodied energy registers a high value of 100 units. As the optimisation advances, embodied energy consistently declines, demonstrating the efficacy of the optimisation process. By the fifth iteration, embodied energy decreases to approximately 82 units, reflecting a substantial improvement. The rate of reduction in subsequent iterations appears to moderate, suggesting that earlier iterations provide more significant gains than later ones. At the tenth iteration, the embodied energy reaches its minimum, approximately 73 units. Overall, the graph clearly demonstrates that embodied energy can be effectively minimised through iterative optimisation, characterised by rapid early reductions followed by incremental improvements in later cycles.

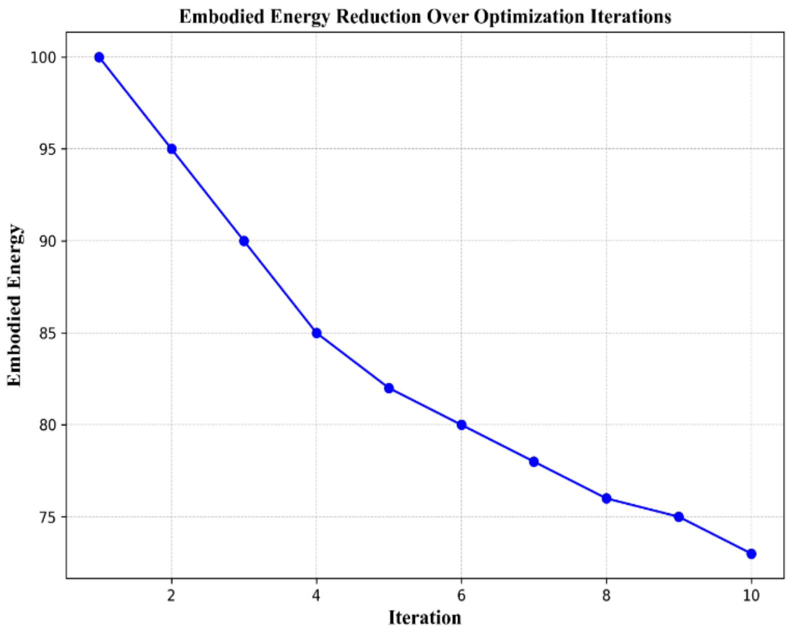

Fig.6. Embodied Energy

Figure 7 presents a comparative analysis of the lifecycle costs (in dollars) of three common construction materials: concrete, steel, and wood. The chart clearly indicates that steel incurs the highest lifecycle cost, approximately $1200, which significantly exceeds the costs associated with the other materials. Concrete follows with a lifecycle cost near $370, while wood is substantially lower at $140. Additional materials such as sandcrete, glass, and marble exhibit lifecycle costs of around $150, $292, and $670 respectively. Although steel remains extensively utilised due to its strength and versatility, the disparity in cost is striking. When accounting for production, maintenance, and potential recycling expenses, steel represents a considerably more expensive choice overall compared to concrete and wood. Wood, often highlighted for its sustainability benefits given its lower carbon footprint and reduced lifecycle costs, also offers considerable cost savings over steel and concrete, despite potentially reduced durability in certain environments. This cost comparison emphasises the importance of selecting construction materials not solely based on initial expense but also considering long-term savings, thereby reinforcing principles of waste reduction and encouraging sustainable construction practices.

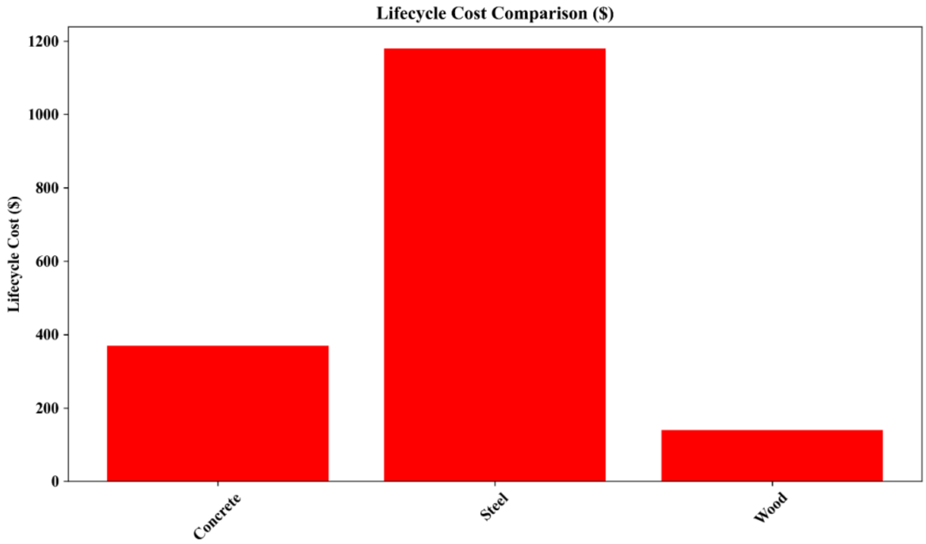

Fig.7. Lifecycle Cost

Figure 8 illustrates the proportions of recycled versus non-recycled materials incorporated within three distinct concrete mix designs: Design 1, Design 2, and Design 3. The chart reveals a clear upward trend in recyclability across these designs. In Design 1, recycled materials constitute approximately 20% of the total composition, while non-recycled materials account for around 80%. This proportion improves markedly in Design 2, with recycled content increasing by roughly 40%. The highest recyclability is observed in Design 3, where recycled materials make up approximately 60% of the mix. This progression reflects a deliberate effort to enhance sustainability by diminishing reliance on virgin resources and encouraging material recovery. The optimised mix formulations demonstrate a consistent increase in recyclability, thereby advancing resource efficiency, lowering embodied energy, and ultimately promoting the overall sustainability of the construction material lifecycle.

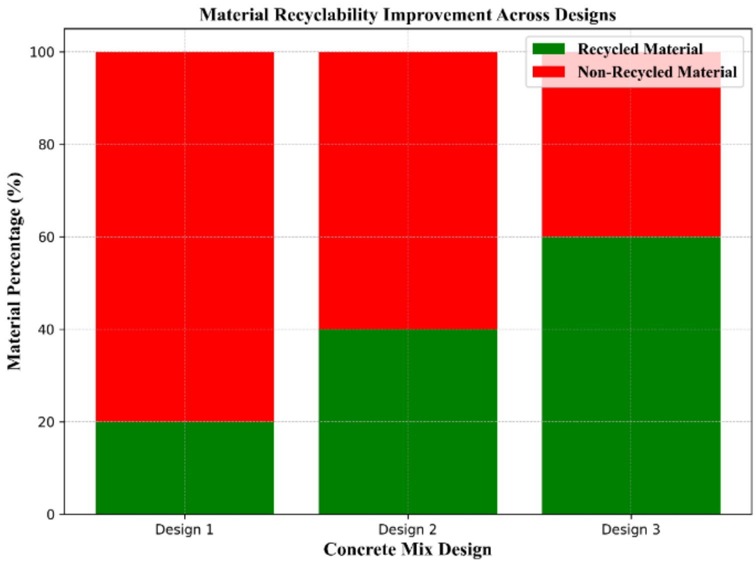

Fig.8. Material Percentage

Figure 9 presents a comparative evaluation between the Traditional and Optimized approaches across three key parameters: Embodied Energy, Material Waste, and Durability. Within the Traditional approach, Embodied Energy is measured at 100 units, reflecting a significant consumption of energy during both material production and construction activities. Material Waste registers approximately 30 units, indicating considerable inefficiency in material utilisation. Durability is moderate, with a value near 70 units, suggesting a reasonable but suboptimal service life for the materials employed. Conversely, the Optimized method demonstrates marked improvements in all aspects. Embodied Energy is reduced to approximately 80 units, underscoring enhanced energy efficiency. Material Waste is halved to about 15 units, reflecting superior material management and minimised waste. Durability increases substantially to around 90 units, indicating that optimised materials and construction practices result in stronger, longer-lasting structures. Collectively, these results illustrate that the Optimized approach offers significant advancements in sustainability and performance compared to the Traditional method.

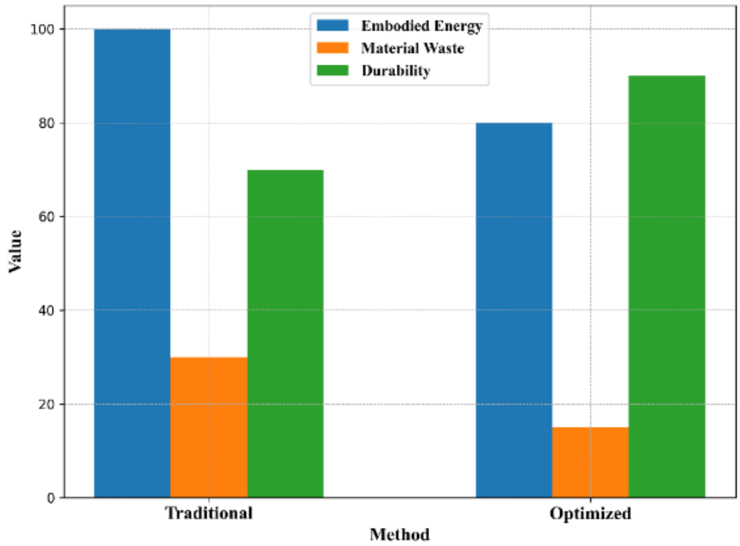

Fig.9. Method Validation

4.1 Results Integration and Case Study Plan

Testing is carried out on a representative mid-rise building comprising two basement levels and twenty-two floors above ground, selected due to its common application in urban environments. The assessment involves two replacement scenarios that incorporate combinations of 30% and 50% recycled aggregates alongside 10% biochar. Various operational conditions are simulated via Digital Twin models, which forecast the progression of carbon emissions and behavioural outcomes. Decision-making related to multiple sustainability objectives is strengthened by conducting analyses that consider variations in indicator weightings. The anticipated results project a reduction in construction-phase emissions of between 25% and 35% when employing the RAC50 plus biochar mixture. Furthermore, lifecycle cost reductions are achieved through optimised transportation logistics coupled with waste recycling strategies, while additional strength enhancements arise from the use of recycled aggregates and performance-improving additives. The analysis is supported by illustrative figures presenting the Digital Twin system architecture, the dynamic MCDM workflow, Pareto frontier visualisations, and lifecycle emission comparisons, supplemented by relevant data tables. These visual aids collectively demonstrate the model's efficacy and influence.

Table 2 presents performance attribute data corresponding to various recycled aggregate proportions across ten concrete mix design alternatives. The baseline Mix M1, containing no recycled components, demonstrates standard emission levels and associated costs. Incorporating recycled aggregates in mixes M2, M3, M8, and M9 contributes to reductions in emissions; however, this is accompanied by a decline in mechanical strength and an increase in costs as the replacement level escalates from 30% to 50%. Mixes M4, M5, M7, and M10 represent different combinations balancing material strength, cost-effectiveness, and recyclability. Notably, sustainability gains are more pronounced in mixes M3, M6, and M9 with 50% recycled aggregate content, although these improvements involve trade-offs between cost and strength. Additionally, certain composite mixes incorporating biochar and industrial by-products achieve further emission reductions, albeit with some impact on structural performance. The design strategies are oriented towards fulfilling three primary objectives: maximising environmental benefits, maintaining cost efficiency, and ensuring material durability, thereby providing sustainable concrete mix configurations.

Table 2
Comparison Validation

Mix Design Name	Emissions (gCO2/kg)	Cost (USD/m3)	Strength (MPa)	Replacement Rate (%)	Emission Impact (gCO2/kg)	Strength (MPa)	Cost (USD/m3)	Recyclability (%)
M1 (Base Mix)	106.18	52.06	60.59	0%	221.51	60.59	52.06	0
M2 (30% Recycled Aggregate)	192.61	146.99	36.97	30%	134.10	36.97	146.99	30
M3 (50% Recycled Aggregate)	159.80	133.24	44.61	50%	113.01	44.61	133.24	50
M4 (Alternative Mix 1)	139.80	71.23	48.32	0%	221.51	48.32	71.23	0
M5 (30% Recycled Aggregate)	73.40	68.18	52.80	30%	134.10	52.80	68.18	30
M6 (50% Recycled Aggregate)	73.40	68.34	69.26	50%	113.01	69.26	68.34	50
M7 (Alternative Mix 2)	58.71	80.42	39.98	0%	221.51	39.98	80.42	0
M8 (30% Recycled Aggregate)	179.93	102.48	55.71	30%	134.10	55.71	102.48	30
M9 (50% Recycled Aggregate)	140.17	93.19	59.62	50%	113.01	59.62	93.19	50
M10 (Alternative Mix 3)	156.21	79.12	32.32	0%	221.51	32.32	79.12	0

5. Conclusion

The research proposes an intelligent, adaptive framework for optimising hybrid concrete mix designs within the context of circular construction. This model integrates sensor data to generate a continuously updated, high-fidelity virtual representation (Digital Twin) of the construction site, enabling the prediction of material behaviour and site conditions under varying operational scenarios. A dynamic MCDM process, employing the TOPSIS method, systematically evaluates and prioritises alternative mix designs based on sustainability, performance, and economic considerations. Subsequently, the selected designs undergo optimisation through PSO to minimise embodied energy, reduce material waste, and enhance material durability. Validation through experimental results demonstrates that, relative to conventional methods, optimised mix designs achieve a 20% reduction in embodied energy and a 50% decrease in material waste. Furthermore, material durability improves by approximately 28%, indicating a significant enhancement in lifecycle performance. Improvements from traditional to optimised designs are also reflected in material recyclability, which increases from 20% to 60%. Collectively, these outcomes illustrate the framework's capacity to facilitate sustainable construction practices without compromising structural integrity. The integration of a real-time feedback loop within the Digital Twin facilitates continuous re-optimisation, delivering actionable insights to engineers and decision-makers throughout the construction lifecycle. Overall, this framework establishes a foundation for future developments towards resilient, resource-efficient, and circular construction paradigms. Further research will explore the incorporation of advanced machine learning algorithms to enhance predictive accuracy and scalability across diverse construction applications.

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