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Circular Economy-Driven Construction Project Management Framework for Minimizing Waste in High-Rise Smart Buildings

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Abstract. The combination of innovative urban development and environmental awareness integrates construction project management with circular economy thinking in vertical, innovative structures. Smart buildings, as a form of modern building and construction process, exhibit excessive energy usage and, in turn, promote material reuse and recycling. The model of innovative construction project management suggested in this study describes waste reduction throughout the lifecycle of high-rise smart buildings powered by advanced technologies and circular economy thinking. Real-time monitoring, control, and management scheduling automation, utilizing IoT sensors, Building Information Modelling (BIM), artificial intelligence analytics (AI), and advanced algorithms for fixed resource automation, enable easy and streamlined resource control within programmable, adaptive, and responsive frameworks. This allows construction to transition to modular systems. Sustainable construction is based on all materials being in closed loops, with multifaceted collaboration among stakeholders involved across multiple levels, focusing on adaptive reuse through modular systems built for deconstruction, where stripping elements are reversed in an assembly line style. Collaborating through all these layers and incorporating phases that extend beyond proper planning (wrap planning) to pre-construction procurement, right up to decommissioning, would allow for reduced emissions, material loss, and more effective environmental impacts by adopting circular economy paradigms. In particular, operational activities that pre-defined waste genres, such as action transforming resources into cost-effective active waste, illustrate the framework's potential in advancing the city's waste management. This research contributes to the ongoing evolution of sustainable construction by applying core concepts of the circular economy, focusing on scaling through technology integration in complex building projects.

1. Introduction

In building, a circular economy (CE) focuses on creating a self-sustaining system by reducing waste, optimizing efficiency, and extending product life through recycling, reuse, and design, as opposed to the linear 'take, make, dump' mentality often employed in modern industries. A CE wants to extend resources indefinitely and seeks to achieve closed loops with no waste created. Regarding the built environment, CE practices can incorporate elements such as modularity or design for disassembly (DfD), the use of renewable materials, and digitally tracking materials throughout their lifecycle [6]. These concepts are critical now more than ever for guiding sustainable development, particularly in dense urban environments where land and resources are limited. Construction activities for high-rise buildings generate substantial amounts of construction and demolition waste [2]. It is also further exacerbated by the project's location in areas with heavy traffic, which makes scaling up very complicated due to urban sprawl; hence, insufficient onsite reuse contributes to material overconsumption [3][7]. In addition, material wastage is not constrained just to the building phase. It starts from procurement through logistics, all the way to purchasing, building maintenance and upkeep, and finally, the dismantling of the constructed building body. Due to the absence of the complex, combined systems to trace the materials being used and monitor waste, one loses a lot of money that can be easily saved by making the process of waste generation easier. Although new construction materials are more sophisticated than conventional ones, cannot significantly solve the issue of material circularity due to the absence of integrative execution of open systems that demand the need to implement the principles of the circular economy in the governing structures [1].

Regarding innovative skyscrapers, there is an existing gap that involves integrating circular economy

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considerations into a project management framework. This framework should guide all phases of IoT-enabled smart buildings toward resources conservation and waste reduction and integrate digital technologies like BIM, IoT sensors, and AI-based analytics to make real-time decisions and trace the materials [4][5]. By coping with the changing environment through adaptive planning and working with other stakeholders, the construction managers could assist in reducing the overall adverse environmental impact and costs of operations of the high-rise buildings [9][11]. Furthermore, this helps meet green building regulations, resulting in enhanced cumulative stakeholder value. Embracing circularity in high-rise construction is now crucial for urban development, as it significantly supports sustainable initiatives [8].

2. Literature Review

Traditional construction project management relies on fragmented workflows and sets a strong emphasis on linear resource use. Such practices, as well as strict scheduling systems, are the reasons that cause inefficiencies in waste management, material ordering and scheduling. Lack of real time ability to monitor the flows of materials significantly enhances wastage of materials in multi-layered projects like high-rise buildings. Unless these projects are dealt with proactively in terms of the sustainable approach, they may end up being overly costly and with long-term effects on the environment. Many case studies have introduced circular economy CE adoption in construction, showcasing its success across different environments [13][14]. Moreover, public-private partnerships with stakeholders during earlier stages have also shown that strategic coherence and cooperation are positive contributors to the success of circular construction, thus demonstrating that greater concern openly drives policy coherence among the diverse forms of joint action that surround it. Researchers have been interested in waste, specifically in high-rise building construction, and have focused chiefly on management systems and technology [10][15]. BIM's visualization capacity enables detailed clash detection and precise estimating, which in turn reduces excess material and enhances logistical efficiency.

Additionally, methodologies based on LCA tools or digital twins are recommended to evaluate waste mitigation in the building lifecycle. Although these tools can be of great benefit, the expense and complexity of these tools coupled with resistance to change in the profession handicap their usage by larger audience [12].

3. Methodology

The researchers utilized a multi-stage systematic research design that entailed literature review, expert opinions, and a case study to develop the proposed circular economy-based framework. To begin with, it is necessary to note that an extensive overview of the current body of literature on the principles of a circular economy (CE), sustainable construction practices, and digital tools (BIM, IoT, and AI) was performed to reveal the main gaps and areas of integration. On the basis of this synthesis, a rough conceptual framework had been elaborated. Next, there were expert consultations and informal interviews with the construction experts and project stakeholders to optimize the components of the framework and make it relevant. The completed framework was subsequently implemented and tested with the help of a real-world case study of a smart high-rise building project to determine its feasibility and usefulness by using specified Key Performance Indicators (KPIs).

High-rise innovative construction projects encompass the entire lifecycle, from planning and design through operation and deconstruction, under the principles of the circular economy (CE). The system proposed will include resource efficiency, closed material flow and real-time analytics. The framework is structured into four core modules: (1) Circular Design and planning, (2) Smart Procurement and logistics, (3) Real-time Waste Monitoring, and 4) End-of-life recovery feedback. All of these modules are equipped with decision support tools that draw data from IoT sensors, Building Information Modeling (BIM), and material tracking systems.

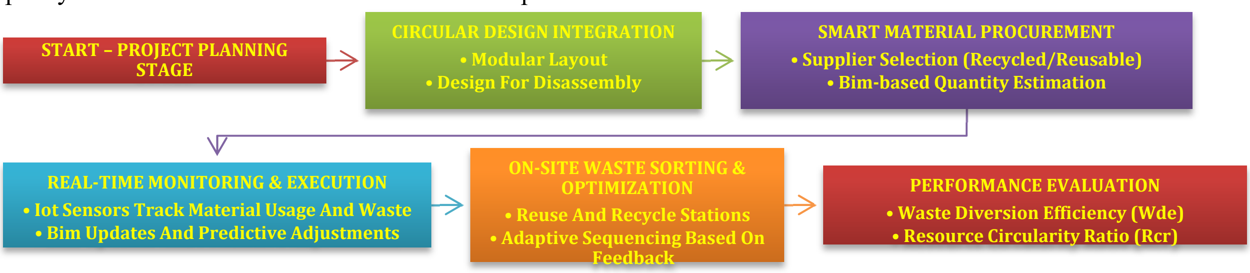

Figure 1: Circular Economy-Driven Construction Project Management Methodology

Figure 1 shows the systematic approach of embedding the circular economy throughout the life cycle of construction project management in smart high-rise buildings. The process of work starts with scheduling of projects, moves in six stages, starting with integration of circular design, innovative materials ordering, real-time execution monitoring (IoT tracked), sorting and optimization of waste on the site, and the final performance appraisal. Every step is meant to reduce the amount of material wastage and redundancy in operations as well as maximizing reuse and efficiency. The circular design is based on modular structures preceded by disassembly planning, whereas innovative procurement is based on the purchase of upcycled and reusable materials on the basis of BIM estimates.

As a measurement tool to prove the effectiveness of the model, applied certain key performance index measurements, such as the waste production measures, resource use measures and the flexibility measure of a system. These included:

Material Waste Intensity (MWI): It is the measure of the quantity of material that is wasted when a structure is made.

Resource Circularity Ratio (RCR): The ratio of materials that are reused or recycled compared to those consumed.

Construction Process Efficiency (CPE): Comparing the planned resource usage and office time against the actual figures.

Smart Traceability Index (STI): How digitally recordable materials have been enables to be tracked through various systems.

Embodied Carbon Reduction (ECR): Reduction percentages in embodied carbon are achieved through the reuse and modification of design elements.

The above KPIs facilitate the quantification of comparison metrics for CE and traditional ergonomic assessment metrics. For example, Material Waste Intensity can be calculated in the following way:

$$MWI = \frac{W_t}{A_f} \quad (1)$$

Where in (1):

W_t is the total waste volume measured in tons or cubic meters

A_f is the built floor area measured in square meters.

Similarly, RCR or Resource Circularity Ratio can be determined as follows:

$$RCR = \frac{M_r + M_u}{M_t} \quad (2)$$

Where in (2):

M_r is the weight of scrapped materials sent to be recycled

M_u is the weight of reused/upcycled materials

M_t is the total mass of any project's constituent material.

Each of these equations provides metrics that enable continual comparisons while allowing flexible control over material usage during the construction stage.

The case study, used to evaluate the proposed circular economy-based project management framework, was conducted on a real-world smart high-rise commercial building project located in an urban metropolitan region in Asia. Due to confidentiality agreements, the exact project name and client details are not disclosed; however, the project consists of a 30-story commercial structure developed by a consortium of private stakeholders with an estimated construction timeline of 24–30 months and a multi-million-dollar budget. The project had involved the stakeholders such as project managers, contractors, sustainability consultants, and technology providers who were to take care of the integration of BIM and IoT.

The project was particularly chosen because it is one that embraces the use of digital technologies in construction, including Building Information Modeling (BIM), IoT-connected materials tracking systems, and construction practices with sustainability in the framework of the principles of a circular economy. The case study allowed observing and analyzing material flow processes, construction schedule, and practices of managing waste on the site under actual operating conditions.

The mixed-methods research methodology was used, which is a combination of quantitative data (e.g., material use, waste production, recycling rates) and qualitative data, collected through site visits and the interactions with stakeholders. Observational records were made on material handling habits, storage procedures, segregation methods and a reduction in waste materials that were adopted at various construction stages. This design has guaranteed more systematic and realistic confirmation of the suggested framework.

4. Results

In a large urban metropolitan region, a smart 30-story commercial building served as a basis for testing the application of project management practices using principles of the circular economy. The project team used the project management framework for various essential phases of the project, including design, procurement, construction, and waste recovery. For the estimation phase and construction simulations, accurate estimates of material quantities were identified using BIM with innovative planning tools that even allowed construction professionals to simulate and model building deconstruction. Purchase orders focused on using suppliers that incorporated recycled or modular elements during production, along with real-time monitoring using IoT sensor technology for material tracking throughout the construction phase.

An impressive reduction in dependence on landfill disposal was achieved, nearly 68% of the total waste generated was recycled within the site borders. This outcome primarily stemmed from the integration of responsive design with circular design add-ons and dynamic adjustments in material flow, enabled by the Material Flow Optimization Engine (MFOE). In order to quantify performance regarding waste reduction, a metric named Waste Diversion Efficiency (WDE) was established through this equation:

$$WDE = \left(\frac{W_r + W_u}{W_t}\right) \times 100 \quad (3)$$

Where in (3):

represent the quantity of material recycled (in tons),

W_u indicates the volume of reused materials (in tons) and

W_t is the total construction waste produced (in tons).

From this metric, a WDE score of 67.9% was derived, which signifies that more than two-thirds of the construction waste was effectively diverted from landfills. Compared to other conventional high-rise buildings of the same size and purpose, the implemented framework showed much better sustainable performance. Traditional high-rise buildings vary in industry standards with 30-40% waste diversion rate. In comparison with these projections, this project managed in accordance with the principles of the circular economy was nearly 70 percent better than these benchmarks. The effectiveness of resources also grew by 25, and the objectives of carbon reduction were met three months earlier than planned. These results demonstrate the benefits of adopting circular construction management methods for advanced urban structures.

Figure 2 illustrates the comparison of waste diversion rates from the construction sector to a high-rise construction project operating under a circular economy (CE) model, focusing on five materials: concrete, steel, wood, packaging waste, and mixed debris. The CE-driven project exceeded the average amount of openly diverted waste. The concrete diversion rate was 45%, and the improvement in diverted concrete was even better at 67%. The steel demonstrated even further improvement, with an even larger increase from 50% to 81%.

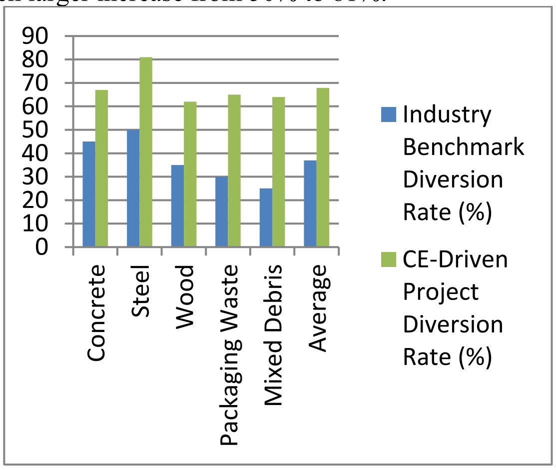

Figure 2. Waste Diversion Comparison by Material Type

5. Discussion

When compared with existing CE implementation frameworks in construction, the proposed approach demonstrates higher integration of digital technologies (BIM, IoT, AI) across all project lifecycle phases. Unlike traditional CE models that primarily focus on material reuse or modular design, framework incorporates real-time monitoring, waste optimization, and decision-support analytics, enabling more precise resource management. For instance, previous studies reported waste diversion rates of 30–50% in high-rise projects adopting CE principles [13][14], whereas the proposed framework achieved a Waste Diversion Efficiency of 67.9%. Furthermore, by combining literature-based design, expert feedback, and case study validation, this framework provides both conceptual rigor and practical applicability, bridging the gap between high-level CE theory and on-site implementation.

The research results pertain to vertical, innovative, or large-scale projects in the construction industry. The reason why the transition towards sustainable practices is important to the industry is that it could be used in parallel to their existing practices. Circular economy approach to project management has been effective in ensuring the attainment of sustainable construction applications that supplements conventional building operations as compared to linear system, which leads to excessive waste in terms of operational and environmental efficiency. On the contrary, closed-loop system enhances flow efficiency.

Like other methods, the proposed framework has some potential effectiveness issues. Related focus on culture in projects, procurement, and stakeholder behaviors presents one distinct challenge for practitioners without any prior experience making these kinds of changes. From my conversations with different stakeholders, I have observed that project teams grounded in more traditional methods can become too attached to existing norms. Additionally, because some geographies contain reusable or recyclable materials, circular procurement is limited in those areas.

6. Conclusion

The study demonstrates the advantages of implementing circular economy principles in construction project management, specifically in relation to innovative high-rise construction. With the circular economy framework, the efficiency of materials used, as well as waste diversion and sustainability performance, improved.

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