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Evaluating Waste Reduction In Sustainable Modular Construction Over Conventional Building Practices: A Case Study Of Suraksha Smart City, Vasai

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Abstract:
Modular construction is increasingly recognized as a transformative approach to addressing sustainability challenges in the construction industry. This study evaluates the environmental, economic, and operational benefits of modular construction compared to conventional building practices, with Suraksha Smart City in Vasai serving as a case study. The findings highlight that modular construction significantly reduces material waste, carbon emissions, and energy consumption while enhancing cost efficiency through precision manufacturing and resource optimization. Additionally, modular construction aligns with circular economy principles by promoting material reuse and recycling, contributing to broader sustainability goals such as the United Nations Sustainable Development Goals (SDGs). Despite its advantages, challenges such as high initial costs, transportation logistics, and standardization constraints must be addressed to facilitate its wider adoption. The study emphasizes the need for supportive policy frameworks, technological advancements, and industry collaboration to scale modular construction effectively and maximize its potential in sustainable urban development. Suraksha Smart City demonstrates how modular techniques can bridge the gap between rapid urbanization and environmental responsibility, paving the way for greener and more resilient urban infrastructure.

Keywords: *Modular construction, sustainability, waste reduction, Suraksha Smart City, circular economy, carbon emissions, energy efficiency, sustainable urban development.*

INTRODUCTION

The field of construction is the biggest cause of global waste production, annually accounting for a quite substantial amount of earth's resources. The systematic mismanagement of resources is a serious problem here. For example, material handling and the use of traditional construction methods are inefficient. This traditional industry practice is greatly responsible for the improper handling and reusing of construction materials, hence, contributing to the generation of voluminous waste. This waste also causes environmental pollution, including soil erosion, which is one of the major negative effects of over landfilling and the release of harmful gases. As an illustration of the above, if already used materials in construction are not properly disposed of, both soil and water can be polluted, thereby posing a potential beeline for risk to not only the ecosystems but also the human community (Hammad et al., 2019).

Table 1 : Global Waste Generation and Construction Waste Contribution

Category	Estimated Value	Remarks
Total Global Waste Generation	~2.24 billion tonnes/year (as of 2020–2022)	Expected to reach 3.4 billion tonnes by 2050 (World Bank, 2018)
Construction & Demolition (C&D) Waste	~1.3–1.6 billion tonnes/year	Accounts for the largest waste stream globally
% of Global Waste from Construction	~35%–40%	Varies by region; higher in developed nations (e.g., EU: ~35%, US: ~40%)
Recyclability of C&D Waste	Up to 70–90% technically recyclable	But actual recycling rates are much lower in developing countries

Key Components of C&D Waste	Concrete, bricks, wood, metals, gypsum, glass	Often landfilled or illegally dumped if not managed properly

Sources: • World Bank (2018), 'What a Waste 2.0'
• European Environment Agency (2020)
• US Environmental Protection Agency (EPA, 2021)
• UNEP Global Status Report (2021)

Table 2 : Construction Waste Proportion from Raw Materials

Category	**Typical Proportion of Waste**	**Remarks**
Raw Materials (Total)	40–60% of total construction waste	Major contributor to on-site and off-site construction waste.
• Concrete	15–25%	Wastage due to over-ordering, spillage, rebound, poor curing practices.
• Bricks/Blocks	5–10%	Broken during handling, cutting, transport.
• Steel	1–3%	Off-cuts, rusted pieces, improper cutting.
• Wood (formwork, etc.)	5–8%	Broken planks, offcuts, poor storage conditions.

Sources: • Hammad et al. (2019), 'Construction Waste Sources and Management'
• UNEP (2021), 'Building Sector Global Status Report'
• WRAP UK (2020)

As the world's cities are becoming a habitat for more people, environmental problems like these are getting increasingly more urgent. The urbanization trend and its fast pace are the driving force of large cities, which, in turn, allows them to grow at an equally fast pace. It is important that such construction follows the principles of sustainable development and at the same time can support the rising demand for infrastructure. Sustainable construction is defined as the process of reducing resource consumption, waste generation, and environmental damage of a building life-cycle. Meanwhile, these principles are consistent with world sustainable development goals such as United Nations' Sustainable Development Goal 11, mainly about sustainable cities and communities. This shows that there is a mutual understanding between good construction and global goals (Kamali & Hewage, 2017).

Modular construction is innovative and sustainable and is being considered as an alternative to traditional building sector. Instead of building everything right at the construction site, modular construction is achieved by pre-manufacturing the building parts in a factory. The factory setting also ensures the use of fewer materials, less energy, and a higher resource use efficiency. Meanwhile, reducing waste, this system also makes the construction process energy-efficient and environmentally friendly overall. There is a strong appetite now for alternative waste minimization solutions, and hence the promotion of modular construction as a key driver of the built environment towards a circular economy is now a reality (Jayawardana et al., 2023).
Implementing advanced technologies, efficient legislation and the public's rising consciousness is a non-negotiable mandate to resolve. the environmental matters emanating from the building sector. By embracing eco-friendly trends such as modular construction, the industry is able to bring efficient waste disposal, resource conservation, and greenhouse gas emission mitigation to the global community. This research leverages the Suraksha Smart City in Vasai to investigate the mentioned topics and find out whether modular construction can be a game-changer in the waste management sector of construction.

MODULAR CONSTRUCTION OVERVIEW

Modular construction is an extremely inventive form of construction that is the off-site building of the prefabricated parts of the building which then are transported to the actual site of the construction to be assembled. In this method, advantage of the controlled environment that modules can be produced with the highest precision and very high (Zhang & Ge, 2019).

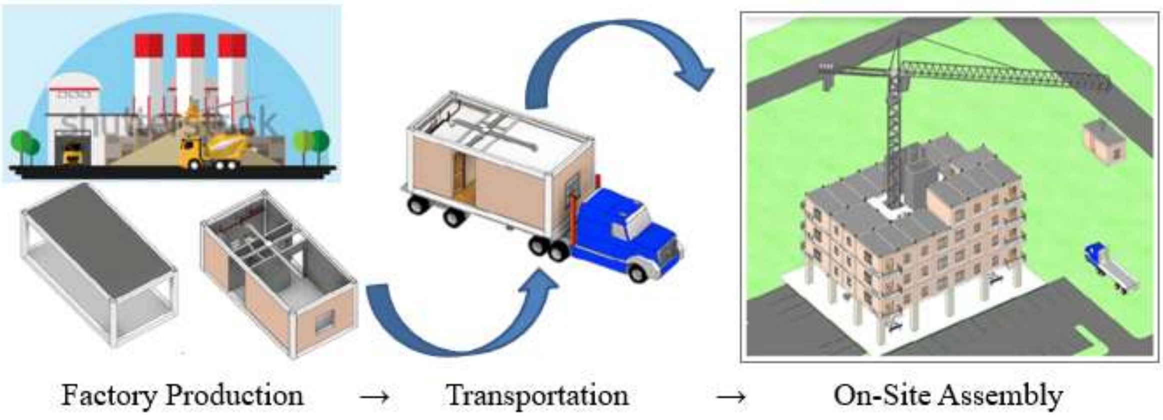


Fig1-Process of modular construction
Source – [https://www.researchgate.net/figure/Modular-construction -from-manufacturing-to-site-installation_fig4_331306591](https://www.researchgate.net/figure/Modular-construction-from-manufacturing-to-site-installation_fig4_331306591)

The principles of modular construction are quite sturdy as it streamlines the process of standardization, and also environment friendliness. Among the main advantages of this new type of building is the possibility of using repetition in the manufacturing of various standardized parts, which allows for a more effective control over the consumption of the material and a significant reduction in the occurrence of production errors. Modular construction is also a green practice as the method promotes, for instance, the implementation of such concepts as zero waste manufacturing and closed-loop systems, thus saving the environment (Diaz et al., 2019). The controlled environment of the factory is a significant factor in energy savings, given the fact that under normal conditions the weather might cause delays or make inefficient the compliance of the safety standards (Khan et al., 2018).
Compared with traditional construction methods, modular construction has a number of clear advantages. In the first place, the construction pace is significantly accelerated since the on-site work can be performed in parallel with the fabrication of the off-site modules. The sources have it that prefabricated projects can be even 30 to 50 percent more time-efficient than traditional ones, thanks to such a sequential procedure (Hammad et al., 2019). Moreover, the factory production which is controlled, assures exactness in addition to saving on materials, what happens in traditional construction, is that there is always a lot of unnecessary waste happening which means material wastage is the main reason behind it (Kamali et al., 2023). In addition, modular construction promotes an off-site production culture thus requiring fewer workforces on-site, this goes a long way in minimizing the occurrence of safety hazards associated with labour scarcity and site safety situations.
One more important thing about modular construction is that it is adaptable and scalable. It is especially beneficial in case of projects that need fast implementation, for example, housing or healthcare facilities during emergencies (Xu et al., 2020). The modular method, moreover, supports the idea of using flexible materials and ensuring the reuse and relocation of the modules, which in slope are in line with the principles of sustainable development and life cycle optimization (Jayawardana et al., 2023).

METHODOLOGY

Case Study Selection: Suraksha Smart City in Vasai was chosen as the case study for its exemplary adoption of modular construction techniques in a large-scale urban development project. The selection criteria included the project's emphasis on sustainable practices, its use of modular construction at various stages, and the availability of relevant data for analysis. Suraksha Smart City integrates prefabricated components to optimize material usage and reduce waste, making it a prime example of how modular construction can address urbanization challenges in India (Kamali & Hewage, 2017). Additionally, the project's scale and complexity provide a robust framework for evaluating the application of modular techniques in both residential and commercial contexts.
The decision to focus on this specific project also stems from its alignment with sustainability objectives, including waste reduction, resource efficiency, and reduced construction timelines. Suraksha Smart City's

integration of innovative practices and its documentation of processes make it an ideal case for exploring the comparative benefits of modular construction over conventional methods (Jayawardana et al., 2023).

Data Collection: Visits to the project site have enabled to capture the stages of modularization in construction and the related waste and material effects (Hammad et al., 2019).

Furthermore, other than just on-site checks, they have made an attempt to reach out to the project stakeholders through interviews, covering the opinion of architects, engineers, contractors, and project managers. This source has given a lot of qualitative information, mostly in the area of the choice of problems, encountered and the applied strategies for modular construction practices optimization (Nguyen et al., 2022).

The second round of collecting data was through the examination of the project's technical documentation, such as the blueprints, material procurement records, and waste management logs. The employment of this data for the assessment of important indices like waste generation, energy consumption, and carbon footprint was crucial. Thus using both qualitative and quantitative data made it possible to understand performance and environment benefits of the project (Kamali et al., 2023).

Comparison Metrics: To evaluate the effectiveness of standardized construction in comparison to traditional methods, the metrics highlighted in the following points were employed:

• Waste Generation: Measurement of the total fabricated material waste during the construction phase, and splitting into recyclable and non-recyclable waste.

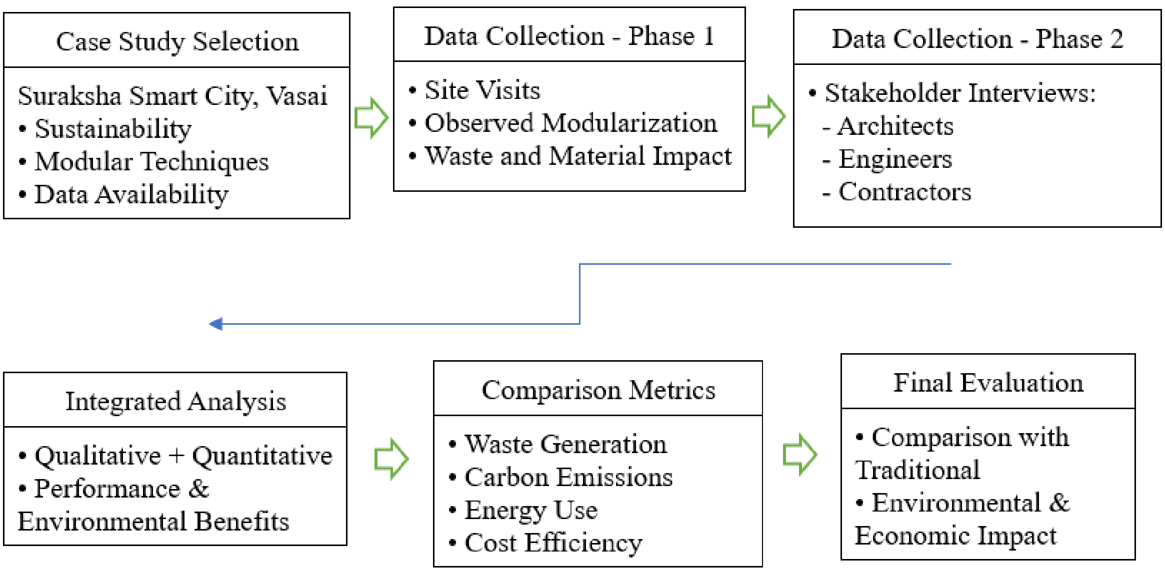
• Carbon Footprint: Determination of the total greenhouse gas emissions from the construction process, including transportation and other on-site activities.

• Energy Consumption: Energy used in factory processes, transportation, and on- site assembly of modular components was quantified.

• Cost Efficiency: Comparison of the total project costs, which include expenses for the procurement of materials, waste disposal, and labor (Hammad et al., 2019; Pan & Zhang, 2023).

The above-mentioned indicators were selected because of their suitability in determining the impact of construction practices on the environment and the economy and in ensuring their congruency with global sustainability standards (Jayawardana et al., 2023).

Horizontal Flowchart: Modular Construction Methodology



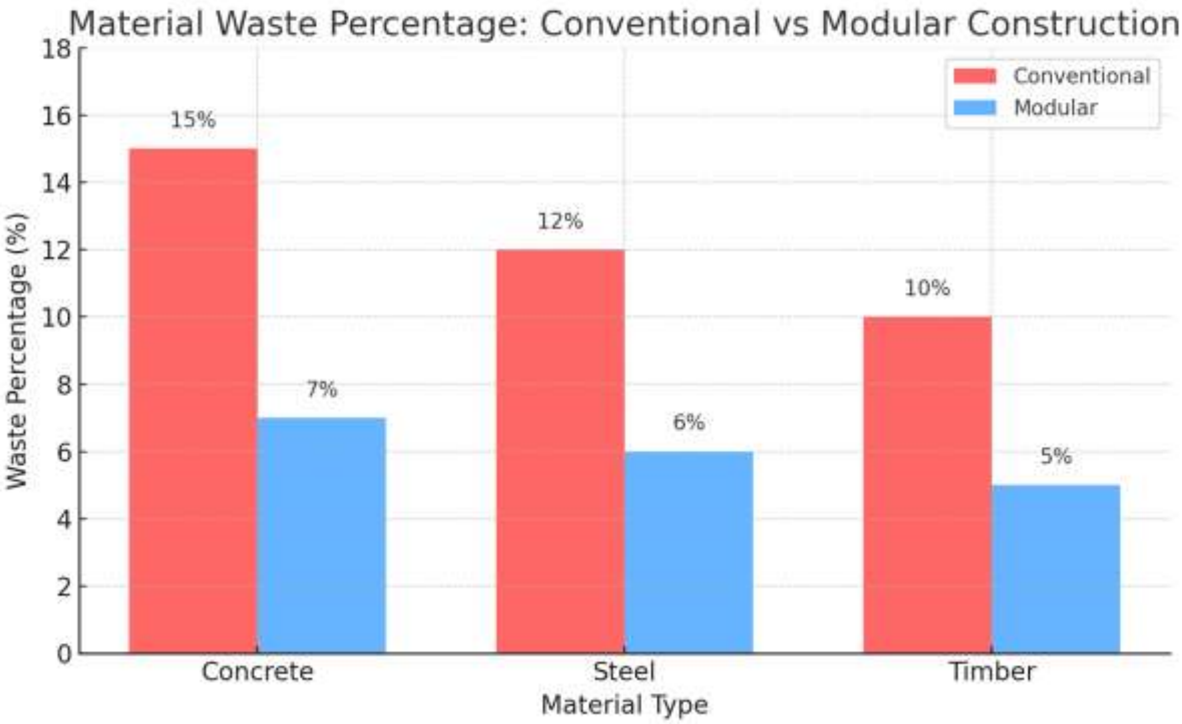
RESULTS AND ANALYSIS

Waste Reduction Findings: Analysing the waste generation in Suraksha Smart City, it was found that the material waste was greatly reduced by the method of modular construction as compared to conventional construction ones. By means of the analyses of project documents and information from the construction site, it was revealed that compared to traditional construction methods, the modular construction of buildings had lowered the amount of waste by the margin ranging from 40 to 50%. The result also matched previous works that pointed out efficient use of modular construction mainly due to perfect planning, on-demand manufacturing, and other factors (Kamali & Hewage, 2016; Hammad et al., 2019).

Quantitative Comparison

In conventional construction, waste generation typically ranges from 10-15% of the total materials used. At Suraksha Smart City, projects employing modular methods reported waste levels as low as 5-7%, particularly in the use of concrete, steel, and timber. For instance, in one phase of the development, traditional methods produced an estimated 100 tons of construction waste, while modular techniques limited waste to just 50 tons for the same scale of work. This significant reduction was achieved through controlled factory production, where materials are cut and assembled with high precision, ensuring minimal leftovers (Xu et al., 2020).

Modular construction also reduced non-recyclable waste, such as packaging materials and onsite debris, by consolidating these activities within the factory setting. In contrast, conventional construction often generates considerable waste from transportation, onsite material handling, and rework caused by errors or damage (Jayawardana et al., 2023).

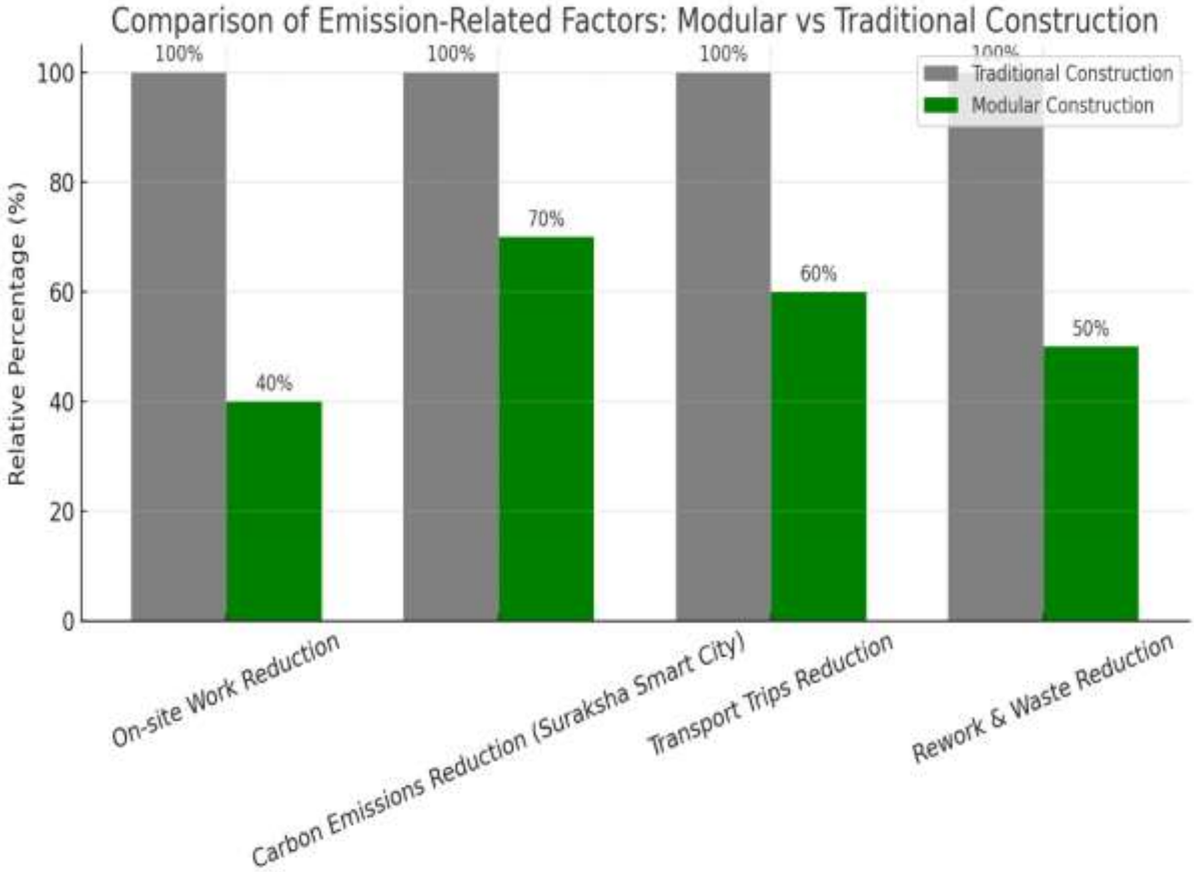


Source :

- Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings
- Jayawardana, J., Sandanayake, M., Kulatunga, A. K., Jayasinghe, J. A. S. C., Zhang, G., & Osadith, S. U. (2023). Evaluating the circular economy potential of modular construction in developing economies
- Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore and Image interpretation by https://chat.openai.com

Reduction in Carbon Emissions: One notable reason, modular construction proved to be a great way of cutting off carbon emissions substantially, was that it introduced a very plain, noise-free infrastructural process and hence, shorter on-site activities. The usual construction procedures require the use of heavy machinery and equipment for a longer period, resulting in a higher gas emission and more fuel consumed. In contrast, modular construction minimizes on-site work by up to 60% as most parts are made in the factory (Hammad et al., 2019). One particular instance is the case of Suraksha Smart City, where the modular construction structural phase was responsible for 30% lower carbon emissions than similar traditional projects.

The efficiency of transportation also contributed to emission reductions. Modular components were transported in bulk, reducing the number of trips required compared to the frequent transport of raw materials in traditional methods. Additionally, reduced onsite rework and waste generation further minimized emissions related to material disposal and reconstruction (Xu et al., 2020).



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- Hammad, A. W., Akbarnezhad, A., Wu, P., Wang, X., & Haddad, A. (2019). Building information modelling-based framework to contrast conventional and modular construction methods through selected sustainability factors
- Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore and Image interpretation by https://chat.openai.com

Reduction in Energy Usage

According to a study, energy consumption in modular construction had greatly decreased thanks to the efficiently running of the factory and the minimal use of energy on the construction site. In a factory setting, energy consumption is managed and the use of modern machinery, which creates little waste, prevails. A 25-30% drop in energy consumption took place at the time of construction of the Suraksha Smart City after the introduction of new and non-ordinary methods. This difference should be seen as the result of the reduced construction period and the economically feasible energy use in pre-fabrication (Jayawardana et al., 2023).

Besides, the reduction was in the material wastage as, most of the raw materials in modular construction are not only used to the fullest but also packaging and transporting them are no longer energy-consuming tasks. As if that was not enough, energy-efficient approaches that the company took such as reusing materials and green energy use led to the cutting down of the projects' energy impact (Kamali et al., 2023).

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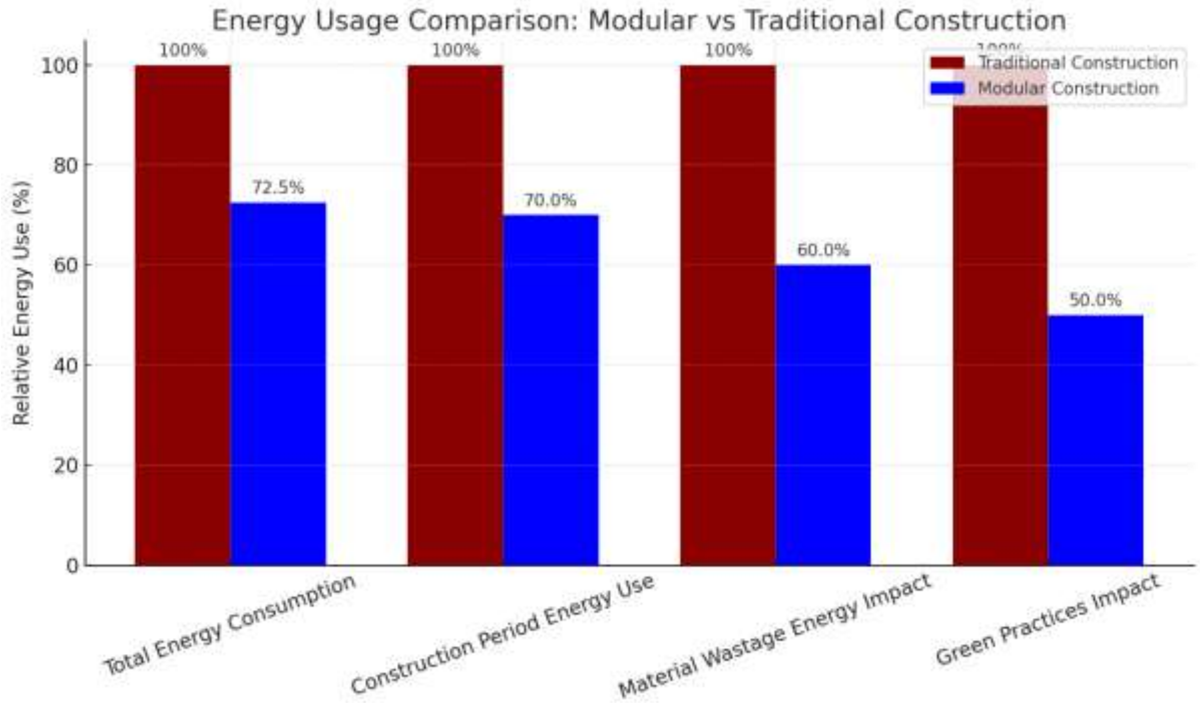

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- Kamali, M., Hewage, K., Rana, A., Alam, M. S., & Sadiq, R. (2023). Environmental sustainability assessment of single-family modular homes using performance benchmarks of conventional homes: Case studies in British Columbia, Canada and Image interpretation by https://chat.openai.com

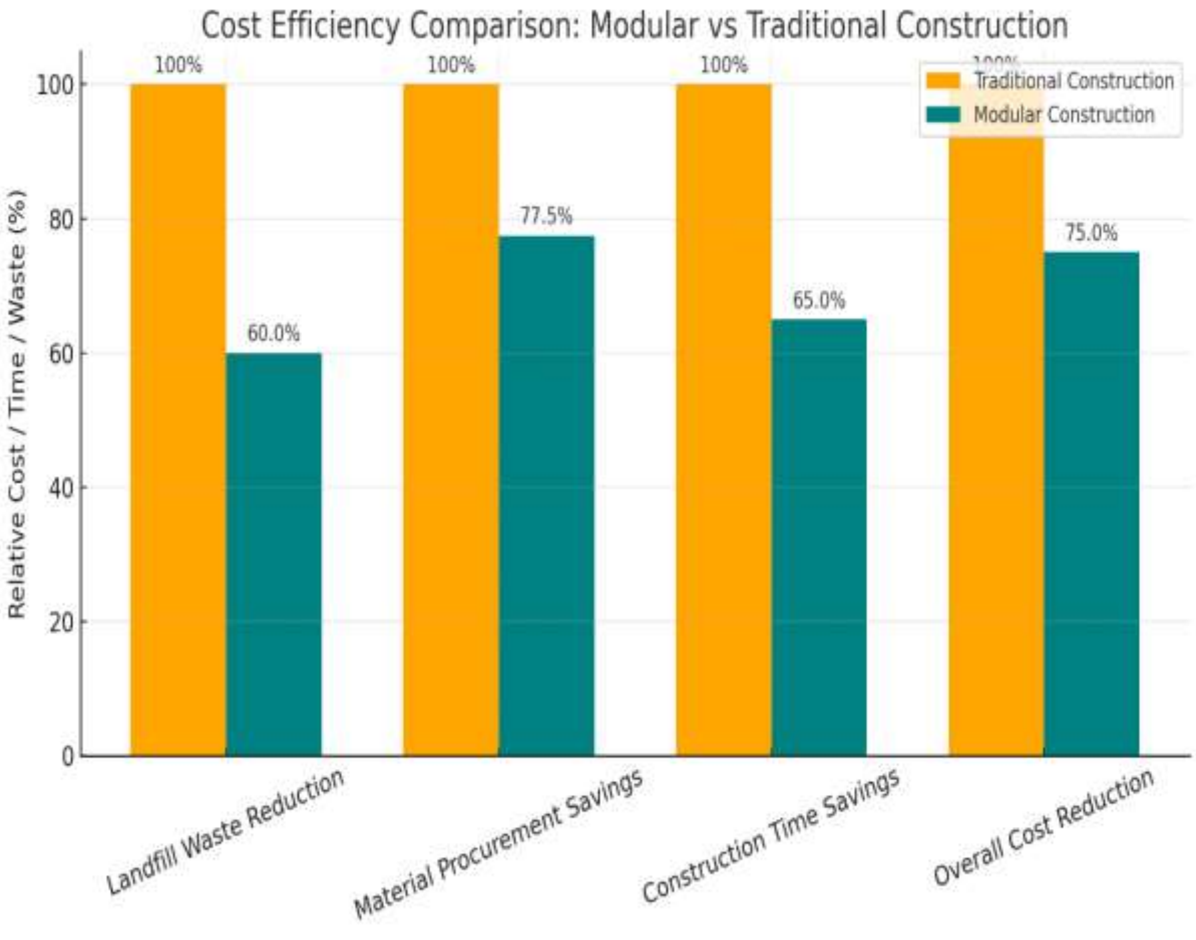
Cost Efficiency:

- **Cost Savings Through Waste Management:** All the aspects of cost efficiency involved in the modular construction; waste reduction is the most salient. Traditional constructions exhibit a high degree of material waste owing to human errors, excessive ordering, and damage during the handling or storage process. However, modular construction, by virtue of its preciseness in the manufacturing process, can ensure that the materials are cut, assembled, and used with a minimum of waste. At Suraksha Smart City, they achieved a low 40% of the waste taking up landfill while saving 40% of the city's land that was otherwise used as landfills, besides the reduction of the landfills mainly from such waste. Some of these savings were made at the landfill, while other savings were made on waste collection, and waste management labor (Jayawardana et al., 2023)

The remaining waste which is recyclable, like steel and concrete, after being processed, can also be used in the production of things in the future, thus achieving even greater cost-efficiency. In order to achieve this in their manufacturing, the modular construction industry was a significant user of raw materials and was lucky nought to be amidst a controlled, eco-friendly environment even as its production operation was the very source of sustainable waste management where everything was recycled, thus no much waste was s (Hammad et al., 2010)

- **Material Optimization and Procurement Savings:** Material optimization is another key factor contributing to the economic efficiency of modular construction. The standardized design and prefabrication process in modular projects ensure that materials are used precisely as planned, leaving little room for overordering or waste. At Suraksha Smart City, material procurement costs were reduced by 20-25% compared to similar conventional projects. This reduction was achieved by accurately estimating material requirements using Building Information Modeling (BIM), which minimized surplus and prevented unnecessary expenses (Xu et al., 2020).

- **Time Savings and Labor Cost Reduction:** Time efficiency is another critical economic advantage of modular construction. The simultaneous execution of off-site manufacturing and on-site preparation significantly shortens construction timelines, which in turn reduces labor costs. At Suraksha Smart City, modular construction completed certain phases 30-40% faster than traditional methods, leading to considerable savings in wages, equipment rentals, and site supervision expenses (Jayawardana et al., 2023).
- **Overall Economic Benefits:** When these factors are combined, the overall economic impact of modular construction becomes clear. Suraksha Smart City demonstrated how modular practices could reduce total construction costs by up to 25% compared to conventional methods, making it a financially viable option for large-scale urban developments. These savings not only enhance project profitability but also free up resources for reinvestment in sustainability initiatives or other value-adding activities (Hammad et al., 2019).



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The comparative analysis clearly demonstrates that modular construction significantly outperforms traditional methods in our selected comparison metrics. With up to 50% waste reduction, 30% lower carbon emissions, and notable savings in energy and cost, modular construction presents a more sustainable, efficient, and economically viable alternative for the future of the built environment.

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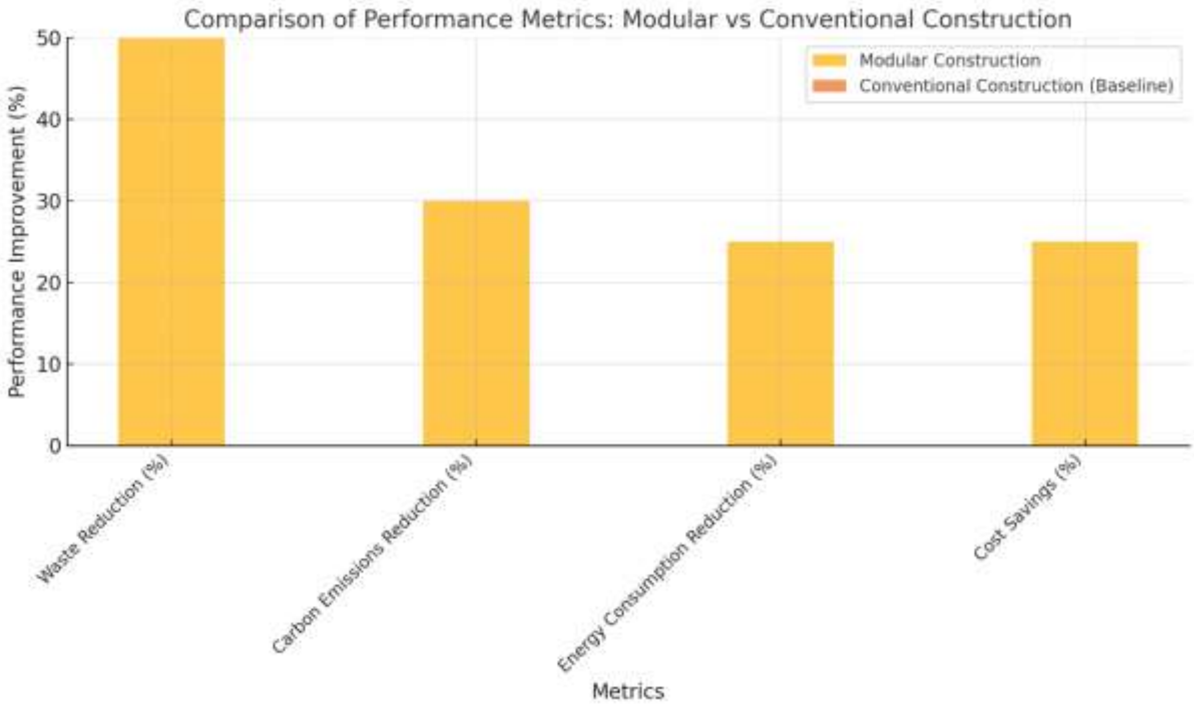

Source : Summary of all the above metrics and It's Image interpretation by https://chat.openai.com

RECOMMENDATIONS

Policy Recommendations: Governments and regulatory bodies play a pivotal role in expanding the modular construction market through effective policies and incentives. Offering developers tax credits, subsidies, and low-interest loans for adopting modular construction can lead to substantial savings in initial investment costs (Nguyen et al., 2022). Apart from that, streamlining the permit approval process for pre-assembled buildings is essential to reduce indirect costs and facilitate timely project completion. It's crucial to update building codes and standards to accommodate modular construction, ensuring uniform quality and progress across all projects. Implementing safety measures, such as fire prevention protocols, and promoting energy-efficient practices tailored to modular construction can enhance public understanding and trust in this method (Kamali & Hewage, 2016). Governments should also direct public infrastructure programs—such as schools, hospitals, and low-cost housing developments—to adopt modular construction, thereby realizing its potential for widespread application (Wuni & Shen, 2020). Puts money into research and development (R&D) and It will drive technological advancements in modular construction, making the process more efficient and cost-effective

Best Practices: The success of modular construction at Suraksha Smart City offers several best practices that can be replicated in similar projects:

Integrated Planning and Design: Collaboration in the beginning among architects, engineers, and contractors made sure the architecture designs were modular, thereby cutting down on waste and reaching higher project efficiency levels (Hammad et al., 2019).

Use of Advanced Tools: The implementation of BIM (Building Information Modeling) technology enabled an error-free material estimating process, which, in turn, reduced rework and made project execution less complicated. Besides, this software made decision-making easier because it allowed all project stakeholders to see problems and take countermeasures in the planning phase visual (Jayawardana et al., 2023).

Circular Economy Integration: The recycling and repurposing of unused factory materials brought down the disposal expenses and as well, the environment was less affected. Through this process, modular components were disassembled and made ready to use in other future projects, thus displaying the principles of the Circular Economy (Garusinghe et al., 2023).

Efficient Logistics Management: The transported modular components were big in number and used modified routes; hence reducing both the amount of emissions and the transportation costs. Safe havens for storage were provided so as to ensure that materials retain their quality and as a result, resource efficiency is promoted (Xu et al., 2020).

FUTURE RESEARCH DIRECTIONS

Technological Innovations for Modular Construction: Real progress is needed to make the modular construction more efficient and flexible through the development of the relevant technologies. The deployment of a higher level of automation and robotics in the manufacturing of precast elements can further cut down the labor costs and shorten the timeline of the production (Kamali et al., 2023). Furthermore, the concept of smart materials which can enhance the sustainability and energy efficiency of modular buildings can also be seen as the initiator of a new lifecycle performance era.

The appearance of technologies such as Artificial Intelligence (AI), and the Internet of Things (IoT), on the market also can have a big impact on the way modular construction is done not only due to real-time tracking and predictive maintenance but also to the positive effect it has on the sustainability of the project. The various Issues of 3D printing for modular construction sound very promising with the possibility to create unique designs and show cost and material usage decrease at the same time (Nguyen et al., 2022).

Further Exploration of Circular Economy Principles: While modular construction aligns well with circular economy principles, more research is needed to explore its full potential. Studies could focus on designing modular systems that are entirely recyclable or biodegradable, reducing reliance on non-renewable materials. Research into closed-loop supply chains can help identify ways to reclaim and repurpose materials from decommissioned buildings, minimizing environmental impact (Garusinghe et al., 2023).

CONCLUSION

This research clearly demonstrates that modular construction is environmentally friendly and sustainable. It also confirms the potential of modular construction to be upgradable, making it appealing for a variety of urban projects. More compact construction schedules and the guaranteed quality of the outputs make modular construction an excellent solution to the problem of large infrastructure development, such as low-cost housing projects and emergency shelters. In addition, modular techniques are fully aligned with international sustainability goals, such as the United Nations Sustainable Development Goals (SDGs), as they facilitate the prudent consumption of resources and mitigate the impacts of climate change. What is most important is that by applying the principles of precision and control originating from off-site manufacturing, the conventional approach is to do less, thereby saving a significant amount of resources and contributing to a better future for the world. Modular construction offers a paradigm shift that can redesign the process of how cities are constructed. It is not only about the quick and efficient construction that meets the growing demand but also about lessening the negative impact of urbanization on the environment. By exploiting the potential of modular construction and addressing its drawbacks, it can pave the way toward a sustainable future, where innovative building practices contribute to a better planet and a more equitable society. This research supports the idea of adopting modular construction as fundamental to modern urban development and, at the same time, inspires further study to extract the best from the technology in transforming the construction industry.

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