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Review

CULTIVATING HOLISTIC APPROACHES TO SUSTAINABLE CONSTRUCTION: INSIGHTS FROM THE REAL-WORLD PROJECTS

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Abstract

This study examines the impact and performance of sustainable building practices through selected case studies. It assesses sustainable design, construction, production, and supply chains, emphasizing the use of advanced materials like Cross-Laminated Timber (CLT) and coated glass to enhance durability and energy efficiency while reducing environmental impact. Nanotechnology and wood innovation in construction are explored alongside insights into reducing energy consumption, utilizing renewable energy, and managing waste across a building's lifecycle. Case studies, including The Edge building in Amsterdam and the Treet building in Bergen, illustrate the efficacy of sustainable practices in creating enduring, eco-friendly structures. The study also highlights successful waste management techniques, exemplified by the Eden Project, demonstrating effective waste reduction, reuse, and recycling in construction. Overall, this research offers a comprehensive view of implementing sustainable building practices to achieve superior performance while minimizing environmental effects.

Keywords: Sustainable construction, construction materials, construction practice, sustainable production, lean construction, energy-efficient building

Derleme

SÜRDÜRÜLEBİLİR İNŞAATA BÜTÜNCÜL YAKLAŞIMLAR GELİŞTİRMEK: GERÇEK DÜNYA PROJELERİNDEN İÇGÖRÜLER

Özet

Bu çalışma, sürdürülebilir bina uygulamalarının etki ve performansını seçilmiş vaka çalışmaları aracılığıyla incelemektedir. Sürdürülebilir tasarım, inşaat, üretim ve tedarik zincirlerini değerlendirmekte, dayanıklılığı ve enerji verimliliğini artırırken çevresel etkiyi azaltmak için Çapraz Lamine Kereste (CLT) ve kaplamalı cam gibi gelişmiş malzemelerin kullanımını vurgulamaktadır. İnşaatta nanoteknoloji ve ahşap inovasyonu, enerji tüketimini azaltma, yenilenebilir enerjiden yararlanma ve bir binanın yaşam döngüsü boyunca atıkları yönetme konusundaki içgörülerle birlikte incelenmektedir. Amsterdam'daki The Edge binası ve Bergen'deki Treet binası da dahil olmak üzere vaka çalışmaları, sürdürülebilir uygulamaların kalıcı, çevre dostu yapılar yaratmadaki etkinliğini göstermektedir. Çalışma ayrıca Eden Projesi ile örneklenen ve inşaatta etkili atık azaltma, yeniden kullanım ve geri dönüşümü gösteren başarılı atık yönetimi tekniklerini de vurgulamaktadır. Genel olarak bu araştırma, çevresel etkileri en aza indirirken üstün performans elde etmek için sürdürülebilir bina uygulamalarının hayata geçirilmesine ilişkin kapsamlı bir bakış açısı sunmaktadır.

Anahtar kelimeler: Sürdürülebilir inşaat, inşaat malzemeleri, inşaat uygulamaları, sürdürülebilir üretim, yalın inşaat, enerji verimli bina

1. INTRODUCTION

In an epoch marred by escalating environmental crises, social disparities, and economic uncertainties, the construction industry stands at a pivotal crossroads. Faced with the challenges of rapid urbanization, burgeoning populations, and dwindling resources, a critical imperative emerges: a fundamental reconfiguration of our construction paradigms (Van Niekerk AJ, 2020). Traditional practices, fixated on short-term gains, have significantly contributed to resource depletion, heightened carbon emissions, and societal marginalization (Huang et al., (2018). The time has arrived for a sweeping, all-encompassing approach—one that not only confronts these issues but also cultivates a sustainable and resilient built environment. The relentless surge in global population forecasts an exponential expansion of urban spaces, intensifying strains on resources and infrastructure. Such rapid urbanization mandates a profound reevaluation of our construction approaches and their intricate interplay with the natural and social milieu (Akinosho et al., 2020). Urgently required are sustainable construction practices that optimize energy usage, curtail waste, and champion social inclusivity. This study embarks on unveiling the transformative potency inherent in holistic sustainability approaches.

By delving into real-world projects that epitomize sustainability, this study showcases innovative design paradigms, construction methodologies, and operational strategies emblematic of holistic sustainability. Moreover, it probes cutting-edge technologies and materials poised to revolutionize the construction domain—from Building Information Modelling (BIM) and advanced data analytics to sustainable building materials and renewable energy solutions (Patrick Bynum, et al., 2013). These technological integrations are evaluated not just for their technical prowess but also through the lenses of their social implications, economic viability, and environmental impact, emphasizing their pivotal role in propelling the industry toward a sustainable future (Thanu H. P., 2022). Unearthing barriers and constraints, this study endeavors to articulate strategies and propose policies fostering a transition toward sustainable construction practices, thereby nurturing an enabling environment for stakeholders across the industry (Tomkiewicz, 2011). Ultimately, this study beckons all participants within the construction ecosystem to action. It underscores the paramountcy of embracing holistic methodologies, fostering collaborations, and dedicating ourselves to long-term sustainability. By meticulously integrating environmental, social, and economic facets across all construction phases—from conception to operation—we have the unprecedented chance to cultivate a construction environment that not only meets present needs but also safeguards the prosperity and well-being of generations to come (Terra dos Santos LC et al., 2023).

1.1. Objective of the Study

This study endeavours to champion holistic sustainability within the construction sector by scrutinizing real-world projects and cutting-edge technologies. It seeks to unearth both exemplary practices and hindrances intertwined with holistic approaches in sustainable construction. Moreover, it aims to distil actionable insights and offer recommendations to stakeholders, facilitating the creation of a constructed milieu that harmonizes environmental stewardship, social equity, and economic viability.

2. SUSTAINABLE CONSTRUCTION: A HOLISTIC APPROACH

The paradigm of sustainable construction signals a profound transformation within the global building industry, aiming squarely at addressing the intricate nexus of environmental, social, and economic challenges inherent in conventional practices. This comprehensive approach necessitates an exhaustive scrutiny across diverse dimensions encompassing materials, energy efficiency, waste management, and societal impacts to establish a robust and enduring framework for sustainable building practices (Akadiri et al., 2012). The manifold advantages of sustainable buildings extend far beyond mere environmental stewardship, positively influencing the quality of life, augmenting work efficiency, and fostering healthier work environments (Akadiri et al., 2012). Furthermore, their multifaceted benefits encompass economic, social, and environmental spheres, manifesting as tangible energy savings, diminished operational costs, mitigated pollution, reduced CO_2 emissions, and heightened occupant health and satisfaction (Hoxha & Shala, 2019). The holistic ethos of sustainable development embraced by the construction industry resonates through its conscientious consideration of economic, social, and environmental facets, epitomizing a holistic sustainability approach (Khan & Ali, 2020).

However, amid the promising prospects of sustainable construction, the industry faces formidable challenges rooted in its environmental footprint, including the specters of climate change, pollution, and energy inefficiency (Rosman et al., 2022). The dynamic landscape of socio-economic evolution and industry advancements necessitates a continuous quest for research, assessment, and the adoption of innovative technologies to fortify the foundations of sustainable development (Gicala & Sobotka, 2018). Sustainable construction transcends environmental concerns to embrace economic and social dimensions. Initiatives like green building certifications have emerged as catalysts propelling sustainability in construction endeavors, aimed at reducing environmental impact and enhancing living conditions for all stakeholders involved in construction projects (Krasae-In, 2016). In the ensuing sections, we meticulously explore the multidimensional facets of sustainable construction, delving into fundamental pillars from materials, energy efficiency, waste management, to societal impacts, culminating in a comprehensive framework for sustainable building practices.

2.1. Green Building Materials

The integration of innovative materials stands as a hallmark in sustainable construction, notably evidenced in the evolution of advanced photocatalytic materials for environmental remediation (Tong et al., 2011). This relentless pursuit for materials aligned with sustainable construction principles emphasizes the burgeoning interest in advanced photocatalytic technologies, particularly those employing metal oxide-based nanomaterials, owing to their eco-friendly traits (Nunes et al., 2021). Moreover, the critical insights shared by Paola et al. (2012) underscore the imperative to address challenges in future research endeavors concerning nano-photocatalytic materials. Similarly, explorations into alternative materials for environmental remediation, such as nanoassembled TiO2 or TiO2 composites, as reported by Windapo & Ogunsanmi (2014), signify the continual quest for eco-conscious alternatives (Windapo & Ogunsanmi, 2014).

Research by Czarnecki & Gemert (2017) posits the perception that innovative building materials/products are inherently 'greener' than conventional counterparts, perpetuating the industry's pursuit of environmentally friendly alternatives. Furthermore, insights drawn from nature and historical durable examples, as highlighted by Sivunen et al. (2013), guide the engineering of sustainable construction materials through innovative approaches, aligning with Subramaniam & Youndt's (2005) assertion that organizations should strive for radical innovation in creating eco-friendly construction materials involving value chain stakeholders.

2.2. Insulation and Energy Efficiency

Efforts to augment building performance and energy efficiency have gravitated towards insulation materials, as emphasized in the comprehensive comparative analysis conducted by Kumar et al. (2020). This scrutiny underscores the pivotal role of insulation materials in curbing energy consumption and underscores their influence on effective construction waste management (Davis, 2010). Zach (2023) further explores the potential adoption of vacuum insulation panels in building construction, exemplifying the industry's shift towards innovative insulation materials to optimize energy efficiency. These findings collectively accentuate the significance of insulation materials in fortifying building performance and energy efficiency across construction practices.

2.3. Ventilation Systems

The exploration of heat recovery ventilation systems, as exemplified by the research conducted by Liu et al. (2015), sheds light on critical design considerations and strategic pathways toward achieving zero-energy buildings. This pioneering work significantly contributes to enhancing indoor air quality while concurrently minimizing energy consumption, aligning seamlessly with the overarching goals of sustainable construction. Liu et al. (2015) specifically focused on assessing the ventilation rates in university dormitories during winter, examining variables such as window orientation, storey placement, and time, all crucial factors impacting ventilation rates. This study offers invaluable insights into the practical implications of ventilation systems in real-world settings, emphasizing the vital importance of optimizing ventilation rates to ensure superior indoor air quality while concurrently minimizing energy usage.

Moreover, the study conducted by Akbari & Öman (2013) is particularly noteworthy as it delves into the effects of heat recovery ventilators on both energy savings and indoor radon levels. The findings revealed a substantial potential for the heat recovery ventilation system to significantly reduce ventilation-related energy losses, amounting to approximately 30 kWh/m2 per year. This underscores the remarkable potential of heat recovery ventilation systems in achieving enhanced energy efficiency, aligning closely with the objective of minimizing energy consumption within the realm of sustainable construction practices. Additionally, the work of Sartori et al. (2012) provides a comprehensive framework for understanding net-zero energy buildings, crucial for contextualizing the significance of research on heat recovery ventilation systems in actualizing the goals of zero-energy construction.

2.4. Waste Management and Circular Economy

The integration of sustainability imperatives, notably conscientious material choices, assumes a pivotal role in mitigating construction waste, aligning seamlessly with the tenets of the circular economy (Romero-Hernández & Romero, 2018). Circular economy principles hold particular relevance in the realm of construction and demolition waste management, proactively addressing the deleterious environmental impacts of such waste (Salleh et al., 2022). An imperative aspect within the circular economy context is the evaluation of waste management systems, elucidating their functionality and efficacy (Chmielewska, 2021). Challenges associated with recycling construction materials, encompassing issues of pollution and contamination, underscore the urgency for sustainable waste management practices (Wali, 2020).

2.5. Societal Impact and Integration

The inclusivity of frameworks in sustainable construction endeavors resonates with the imperative to harmonize social and economic dimensions, integrating considerations of social equity, economic viability, and long-term sustainability (Folke et al., 2021). This holistic approach underscores the imperative of amalgamating societal well-being with environmental objectives, emphasizing the necessity to address multifaceted dimensions within sustainable construction (Srivastava et al., 2021). The societal footprint of sustainable construction lies in the equilibrium sought between economic, social, and environmental interactions throughout the lifecycle of construction projects (Srivastava et al., 2021). Notably, the transformative impact of Construction 4.0 on environmental, economic, and social sustainability underscores the interconnectedness of these dimensions within construction practices (Balasubramanian et al., 2022). Moreover, the prism of sustainable entrepreneurship accentuates the fusion of economic opportunities with broader societal considerations, advocating for a multi-dimensional approach (Lans et al., 2014). Validated competence frameworks for sustainable entrepreneurship further underscore the necessity of integrating social, environmental, and economic factors in entrepreneurial pursuits (Ploum et al., 2017).

3. METHODS

The methodology for this research encompassed a comprehensive review and analysis of real-world projects, drawing insights from the available literature and case studies. The process was divided into several key steps.

3.1. Data Collection

The research began with the systematic collection of data from academic publications, scholarly articles, and real-world case studies. These sources provided a wealth of information on sustainable construction practices, environmental impacts, and social implications.

3.2. Selection of Case-study

The selection of case studies was a meticulous process aimed at encompassing a broad spectrum of sustainable construction practices. Criteria for inclusion were rigorously defined to ensure a comprehensive representation of diverse approaches, the following criteria were considered for the selection of the case studies;

i. ***Variety in Practices***: Encompassing energy-efficient designs, innovative material utilization, waste reduction strategies, and social sustainability initiatives.
ii. ***Geographic Diversity:*** Ensuring diverse representation to capture regional influences, considering projects from various locations and diverse socio-economic backgrounds.
iii. ***Project Scale:*** Balancing large-scale infrastructure projects with community-driven initiatives and innovative small-scale endeavours for a holistic overview.
iv. ***Long-Term Impact:*** Prioritizing studies that showcased sustained sustainability impact, emphasizing practices with demonstrable longevity and adaptability.

3.3. Literature Review

A thorough literature review was conducted to gain an understanding of the existing body of knowledge regarding sustainable construction practices. This included studies related to green building materials, and construction techniques.

3.4. Data Analysis

Content analysis was employed to scrutinize the collected data. Thematic analysis was utilized to identify recurring themes and patterns within the literature. Additionally, categorical coding was employed to categorize the findings from the case studies into distinct groups based on their subject matter. The following processes were considered for the data analysis;

i. ***Thematic Analysis:*** Data collected underwent a rigorous thematic analysis. Categorization into recurring themes allowed for the identification of patterns, challenges, and successful strategies within each case study.
ii. ***Cross-Case Synthesis:*** Synthesizing data from various studies enabled the extraction of overarching insights and comparisons. This process involved identifying commonalities, differences, and emergent trends across diverse sustainable construction practices.

iii. ***Validity Checks:*** To ensure the reliability and credibility of findings, the research employed various validation methods. Triangulation, involving multiple data sources, viewpoints, and methodologies, was utilized wherever feasible.

iv. ***Ethical Considerations:*** The study adhered to stringent ethical standards in handling information. Proper citations and acknowledgments were made to respect the intellectual property rights of the sources used.

3.5. Data Interpretation

The data, once analysed, was interpreted to extract meaningful insights and findings. This stage involved assessing the implications of various sustainable practices on construction, environmental sustainability, and social equity.

3.6. Narrative Synthesis

A narrative synthesis was conducted to weave together the insights derived from different sources. This involved crafting a cohesive narrative that highlighted the linkages between various sustainable construction practices and their impact on the built environment.

3.7. Comparative Analysis

The research employed comparative analysis to draw connections and distinctions between different sustainable practices and their outcomes. This approach facilitated a holistic view of the diverse strategies used in real-world projects.

3.8. Limitations Acknowledgment

This methodology acknowledges inherent limitations, including potential biases in source selection, data availability, and the subjective nature of qualitative analysis.

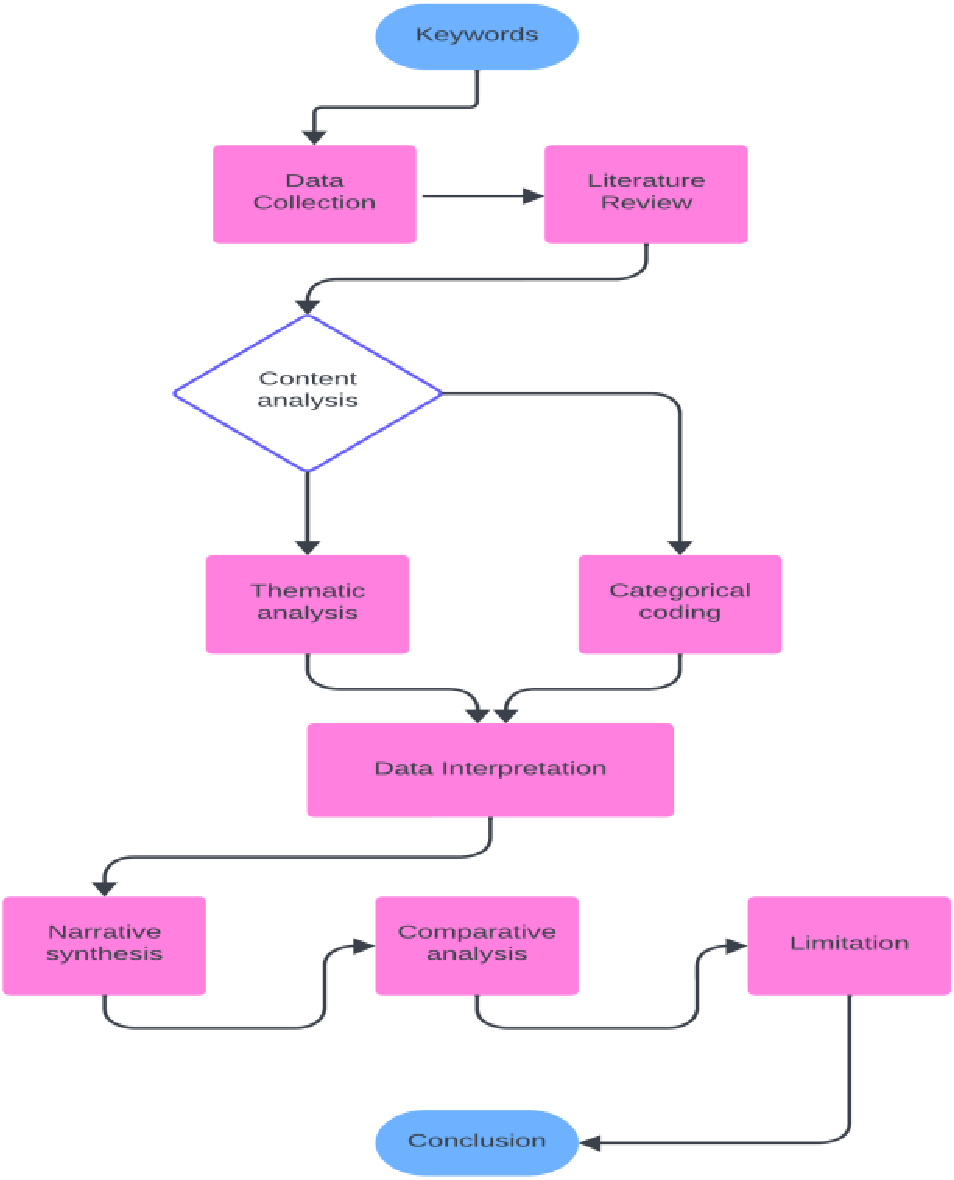

Figure 1. Flow of the study

4. CONSTRUCTION PRACTICES AND RELEVANT CASE STUDIES

4.1. Sustainable Production/Manufacturing

Cutting-edge construction materials represent an innovative approach to improving the performance and sustainability of buildings and infrastructure. These materials offer a wide range of benefits, including increased durability, enhanced energy efficiency, and a reduced environmental impact achieved by lowering greenhouse gas and carbon emissions output. Notably, some of these materials have the unique capability to capture carbon from the environment, as pointed out by Kuperstein-Blasco (2022). For example, consider Cross-Laminated Timber (CLT), a manufactured wood material produced from sustainable wood fibers. This material possesses exceptional strength and stability while also acting as a carbon sink, making it particularly suitable for tall buildings and large structures. Another noteworthy example is coated glass, where nanotechnology is applied to the glass surface. This technology significantly extends the glass's lifespan, as indicated by Jones et al. (2015), while simultaneously improving a building's energy efficiency by reducing heat transfer through the glass, as highlighted by Yasin and Atiyat (2017). Both these materials are environmentally friendly and have the capacity to encourage the adoption of more sustainable construction methods.

4.1.1. Nanotechnology

Nanotechnology involves the precise manipulation of molecules and atoms at the atomic level using engineering techniques, as outlined by Hossain and Rameeja (2015). This field of science and engineering has attracted significant attention and has found diverse applications in civil engineering (Hossain and Rameeja, 2015). This field of science and engineering has made a significant contribution to the progress of construction materials, resulting in innovations like fire-resistant steel, durable concrete, and enhanced glass materials. Glasses are commonly used construction material for their ability to bring natural lighting into buildings. It is therefore, susceptible to degradation and corrosion due to the interaction of oxygen and water in the atmosphere (Altavilla, 2006). The integration of nanotechnology offers the potential to improve the structural composition of the glass materials, thereby extending their durability, lifespan and mitigating issues related to corrosion.

i. Case of study: Edge building Amsterdam

The Edge building, situated in Amsterdam, Netherlands, is an exemplary case of technology adoption. Its façade, covering approximately 13,000 square meters, consists of a combination of glasses in various shapes and sizes, ingeniously arranged within a solid aluminum panel framework. The design predominantly utilizes glass to maximize natural daylight illumination. Additionally, the façade is coated to serve a dual purpose: to attenuate external noise and to limit the ingress of solar radiation into the building. This strategic coating enhances the building's energy efficiency, consequently reducing overall energy consumption by diminishing the reliance on air conditioning systems. Notably, advances in nanotechnology, as highlighted by Yasin and Atiyat (2017), have led to the development of ultra-thin coatings for window glass. These coatings possess the capability to selectively filter out undesirable infrared light frequencies, effectively curbing heat penetration into the building.

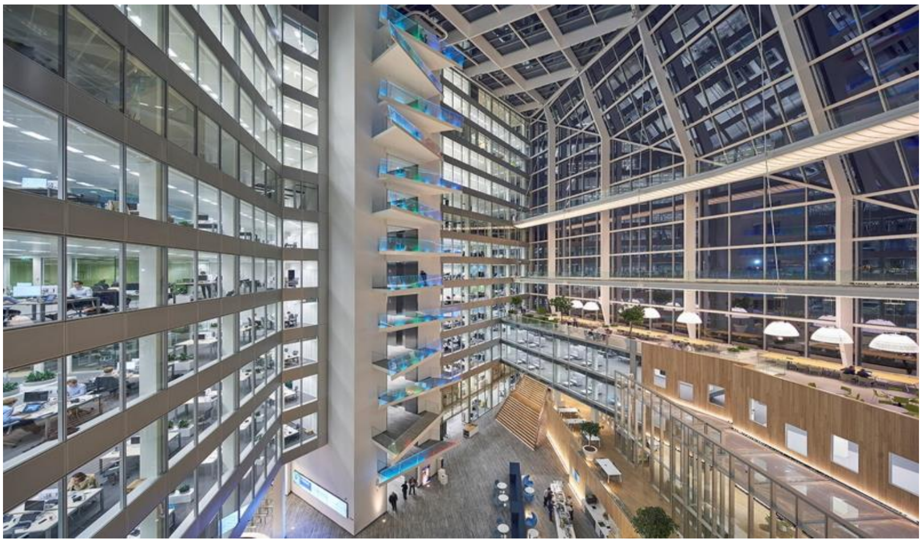

Figure 2. The Edge, Amsterdam (Garofalo, 2015; Jalia and Ramage, 2016)

ii. Benefits

Integrating nanotechnology into glass production yields substantial benefits, notably in the development of energy-efficient glass, capable of reducing energy loss by an impressive 80% (Noh et al., 2020). These advanced glass solutions offer not only energy savings but also exceptional transparency and reduced heat transmission when compared to conventional insulated glass (Kumar et al., 2020). Furthermore, they effectively reflect visible light while inhibiting the transfer of heat, infrared rays, and harmful ultraviolet light. An investigation by Jones et al. (2015) underscores the positive impact of nano-silica intumescent layers on glass properties, conferring remarkable fire resistance that can endure for up to three decades.

iii. Challenges

The rapid proliferation of nanotechnology has raised valid concerns regarding potential adverse effects on human health and the environment. Recognized by Hischier et al. (2017), Life Cycle Assessment (LCA) emerges as the most suitable approach for evaluating the environmental performance of nanoproducts. According to Pini et al. (2017), environmental analysis was conducted for one meter square of this specialized glass. The findings reveal that the production stage (65.08%) and the usage stage (28.16%) impose the most significant impacts on the environment, followed by end-of-life considerations (6.08%) and installation (0.67%).

iv. Key Finding

The Edge building serves as a compelling example, illustrating that the integration of nanotechnology in construction industry can lead to the creation of more durable, energy-efficient, and eco-friendly structures. Such advancements contribute significantly to the endeavor of building a sustainable and environmentally responsible future.

4.1.2. Innovation

The utilization of wood in construction is regarded as an innovative approach that diverges from traditional building practices reliant on materials like steel and concrete. In the 19th century, traditional timber constructions saw reduced usage due to the emergence of steel and reinforced concrete construction techniques (Grabner et al., 2017). Working with wood is now considered a fresh and forward-thinking concept, primarily due to the required organizational processes and technical expertise. Wood presents notable advantages, including lower carbon emissions, reduced greenhouse gas output, and the ability to sequester carbon (Kuperstein-Blasco, 2022). The incorporation of wood in construction actively addresses contemporary concerns related to climate change and sustainability. It does so by endorsing sustainability in forest practices and effectively reducing the footprint of carbon in the construction industry.

i. Case of Study: Treet building, Bergen

The Treet building, located in Bergen, Norway, stands as a remarkable exemplar of wood innovation. This 14-story residential edifice was meticulously constructed using cross-laminated timber panels, along with glulam columns and beams. The choice of these materials was guided by their exceptional durability, strength, and sustainability. Notably, the incorporation of wood in the Treet building led to a net sequestration of carbon, surpassing the emissions generated during the construction process, effectively rendering it a carbon-negative structure. Furthermore, Treet boasts energy efficiency, thanks to a sophisticated energy management system that curtails energy consumption and carbon emissions. The construction of Treet serves as a beacon of innovative wood usage, paving the way for the creation of eco-friendly and energy-efficient structures.

Figure 3. The Treet building, Bergen, Norway (Kjolberg, 2017)

ii. Benefits

In general, the integration of wood into construction represents an inventive and advantageous approach that simultaneously addresses significant environmental and societal concerns (Kuperstein-Blasco, 2022). Moreover, Kuperstein Blasco et al. (2021) suggest that wood offers preventive benefits over concrete materials, encompassing enhanced health outcomes and mitigation of climate change effects. In Finland, wood finds extensive popularity as a construction material, contributing to the development of multi-storey residential buildings, sports centers, commercial structures, and bridges (Hurmeskoski, 2016). By implementing the Wood-frame Multi-storey Construction (WMC) innovation system, a lot of apartments have been successfully constructed, bolstering wood's standing and reputation within the construction industry. Additionally, the adoptiop of wood in construction can help reduce indoor moisture levels, thereby preventing bacterial growth, improving indoor air quality, and enhancing thermal comfort (Tran et al., 2020).

iii. Challenges

Despite its numerous advantages, the widespread utilization of wood in construction encounters several challenges. Foremost among these challenges is the potentially high cost of wood, often exceeding alternative options by up to 25%. This cost disparity can render wood cost-prohibitive for some construction projects (Akanbi and Zhang, 2020). Furthermore, wood is combustible, necessitating stringent fire regulations for wooden structures, which can pose challenges for builders and architects. Additional challenges encompass the need for regular maintenance, the risk of deforestation, and wood's vulnerability to pests and moisture-related issues.

iv. Key finding

Wood stands as an eco-friendly and sustainable building material, offering a low-carbon alternative to other construction materials. The Treet building which is located in Bergen serves as a compelling example of innovation that champions sustainability in construction practices.

4.2. Sustainable Design and Construction

Sustainable design and construction practices focus on minimizing the negative environmental and societal impacts of buildings and infrastructure while enhancing the well-being of occupants. These methods involve the use of eco-friendly, energy-efficient, and resource-efficient materials and techniques (Priavolou et al., 2021). Fundamental principles of sustainable design and construction encompass the reduction of energy usage, the incorporation of renewable energy resources, waste and pollution reduction, and the encouragement of biodiversity. These practices consider a building's entire life cycle, from initial design to eventual demolition, to ensure lasting sustainability (Khan and Ali, 2020). Embracing sustainable design and construction approaches is crucial for promoting environmentally responsible construction methods that benefit both the planet and human well-being (Hussain et al., 2023).

4.2.1. Zero Carbon and Energy Efficient Building

Buildings worldwide account for about 40% of total energy consumption and contribute to 28% of carbon emissions, making them significant contributors to global climate change (Clarke et al., 2023). Addressing the challenges of global warming and excessive energy consumption requires a shift toward constructing Zero Carbon Buildings (ZCBs). These structures are highly energy-efficient, generating on-site energy or obtaining it from renewable, carbon-free sources to offset annual carbon emissions from their operations. The adoption of ZCBs has the potential to significantly reduce greenhouse gas emissions and mitigate the effects of climate change (Trofimova et al., 2021).

i. Case of Study: Edge building Amsterdam

The Edge building in Amsterdam is an exemplary model of a sustainable and energy-efficient office structure. It boasts an outstanding BREEAM score of 98.36%, establishing itself as one of the world's most environmentally conscious buildings. The building's design incorporates a diverse array of energy-saving technologies, strategically integrated to dramatically reduce energy consumption. Notably, it harnesses solar energy by installing solar panels on its roof and façade, producing surplus energy. These panels also serve as effective sunshades, reducing the need for cooling by minimizing direct sunlight penetration. The Edge building features an intelligent lighting system connected to its building management system, optimizing lighting with daylight and motion sensors, and allowing occupants to customize their lighting and temperature preferences to minimize energy wastage. Additionally, the building employs an advanced Aquifer Thermal Energy Storage (ATES) system that significantly reduces heating requirements by up to 40%, enhancing overall energy efficiency. The Edge building sets a precedent for sustainable design and construction, emphasizing energy efficiency and environmental responsibility.

Figure 4. The Edge, Amsterdam. (Jalia and Ramage ,2016)

ii. Benefits

Approaching sustainability comprehensively, eco-friendly buildings can significantly reduce their ecological impact and offer long-lasting benefits (Lu & Deng, 2017). Research findings regarding occupants' perceived thermal comfort in green buildings vary. For instance, Ravindu et al. (2015) have noted that some studies suggest improved thermal comfort for people in green buildings. In a case study conducted in Korea, two green-certified buildings were found to have higher occupant satisfaction levels with regard to thermal comfort, lighting, furniture, and cleanliness compared to two non-rated offices (Altomonte, S. et al., 2017). Conversely, as per Kim et al. (2015), other case studies have indicated that LEED-certified buildings generally outperform non-green buildings in terms of the thermal environment. Despite the contrasting findings on thermal comfort, a systematic review conducted by Khoshbakht et al. (2018) revealed that all LEED buildings tend to offer superior air quality compared to conventional buildings.

iii. Challenges

Overcoming the challenges of achieving zero carbon and energy-efficient buildings includes addressing the significant upfront costs associated with technologies like insulation, solar panels, and energy-efficient HVAC systems (Liu et al., 2022). Challenges also arise from the lack of standardized practices, inadequate building codes, maintenance requirements, and changes in occupants' behavior.

iv. Key finding

The Edge building serves as a notable example of sustainable architecture by incorporating various features and technologies to minimize its environmental impact. It establishes a benchmark for future sustainable construction practices with its innovative design and use of renewable energy sources.

4.2.2. Sustainable Waste Management

Sustainable development necessitates the integration of sustainable construction waste management practices. The construction industry is one of the world's most significant waste generators, with the potential to significantly impact the environment (Kabirifar et al., 2020). Sustainable construction waste management practices prioritize eco-friendly waste management techniques throughout the construction process, from design to demolition, in contrast to traditional practices that often involve waste disposal in landfills or incineration. Presented below are examples of sustainable waste management methods.

i. Case of Study: Eden Project Cornwall

The Eden Project in Cornwall is a compelling example highlighting the advantages of sustainable waste management practices in construction (Mysen, 2012). Throughout its construction, this project, featuring two large biomes designed to house tropical and Mediterranean plant species, embraced sustainable waste management techniques. These methods focused on waste reduction, reuse, and recycling, resulting in an impressive 80% reduction in the project's environmental footprint. As a renowned tourist destination, the Eden Project underscores the importance of incorporating sustainable waste management into construction projects.

Figure 5. The Eden Project in Cornwall (Baczyńska and Lorenc, 2012)

ii. Benefits

a) *Reduce:* The approach of minimizing waste involves reducing the consumption of raw materials and resources to limit the initial generation of waste. Activities like purchasing products with minimal packaging, utilizing reusable items, and optimizing energy and water usage contribute to promoting sustainability. By diminishing waste production, we can protect natural resources, lower emissions of greenhouse gases, and reduce the necessity for disposal facilities (Tolba et al., 2020).
b) *Reuse:* Reusing entails identifying fresh applications for materials and products that might otherwise be discarded, either in their original state or by adapting them for different purposes (Huang et al., 2018). The act of reusing items aids in reducing waste and the demand for new resources. This can be achieved through fixing broken objects, contributing usable items in good condition, or selling them.
c) *Recycle:* Recycling constitutes the transformation of waste into novel materials, thus lessening the requirement for new raw materials and the preservation of natural resources (Huang et al., 2018). Recycling provides a range of advantages, including diverting less waste to landfills and incinerators, conserving natural resources, and consuming less energy. Other notable practices encompass material selection, designing for deconstruction, and the implementation of suitable disposal methods.

iii. Challenges

Sustainable waste management aims to mitigate the negative environmental impact of waste and promote sustainable growth. Challenges include hazardous waste management, raising awareness, allocation of resources, development of effective policies, encouraging public participation, and addressing the effects of climate change (Cheng et al., 2022). Successful implementation of sustainable waste management practices that support sustainability requires collaboration among various stakeholders. Challenges may also stem from inadequate management practices, inappropriate recycling technologies, and an underdeveloped market for recycled products.

iv. Key finding

As exemplified by The Eden Project in Cornwall, the adoption of sustainable waste management practices can lead to reduced waste generation, improved resource efficiency, and diminished adverse environmental impacts during building operations. The incorporation of the reduce, reuse, and recycle approaches in the construction sector can result in a more sustainable and environmentally friendly end product (Tolba et al., 2020).

4.3. Defect Analysis

Defect analysis in the construction field involves the inspection and evaluation of any faults or defects in a construction project. The primary objective is to identify issues or faults as early as possible to prevent them from becoming more costly and time-consuming to rectify. This process typically includes a comprehensive assessment of the construction project, covering aspects such as workmanship quality, materials used, and construction techniques (Li et al., 2022). Experienced inspectors or engineers with expertise in identifying construction flaws often conduct these examinations.

4.3.1. Lean Construction

Traditional construction methods tend to focus on individual tasks and their efficiency, often overlooking the overall project's success. They are centered around transforming inputs into outputs without giving much consideration to the project's overall performance (Koskela, 2020). In contrast, lean construction strives to minimize waste, enhance efficiency, improve productivity, reliability, and workflow, ultimately reducing costs and increasing profits (Babalola et al., 2019). One example of the lean construction approach is the last planner system, a collaborative planning strategy that involves all project stakeholders in the planning and execution phases. It ensures that all prerequisites and constraints are taken into account during the initial planning stages, thus promoting uninterrupted and on-schedule project completion.

i. Case of Study: Royal Adelaide Hospital

The Royal Adelaide Hospital in South Australia, with a construction cost of $2.4 billion, serves as a noteworthy example of lean construction practices. The project team employed the "last planner" approach to foster collaboration and communication among project stakeholders. This approach entailed the creation of a detailed schedule updated on a weekly basis, with input from all involved parties, including those responsible for the project's final stages. By adopting this approach, the project team could proactively identify and address potential delays, reduce wastage, and enhance overall efficiency. Furthermore, the construction project embraced off-site prefabrication and modular construction techniques, which resulted in a reduction in on-site labor requirements and material waste while simultaneously elevating construction quality. The assembly of substantial portions of the hospital within a controlled factory environment enabled the team to work with increased efficiency.

Figure 6. The Royal Adelaide Hospital in South Australia (Sexton, 2017)

ii. Benefits

The Last Planner System (LPS) offers several advantages, including heightened collaboration among stakeholders, increased predictability in project timelines, and a reduction in construction-related waste (Wu et al., 2019). The implementation of LPS facilitates the delivery of sustainable facilities by enhancing execution coordination, providing management flexibility to accommodate changes effectively, and addressing new constraints with greater ease (Francis & Thomas, 2020).

iii. Challenges

Challenges associated with the adoption of lean construction practices such as the Last Planner System encompass resistance to change, limited availability of relevant data, uncertainty and variability, coordination among multiple trades, and a dearth of experience and expertise in its application.

iv. Key Finding

Lean construction, exemplified by the application of the Last Planner System, contributes to sustainability by minimizing waste, enhancing efficiency, and fostering collaboration within construction processes, as demonstrated in the case of the Royal Adelaide Hospital.

4.3.2. Total Quality Management

Eltawy and Gallear (2017) emphasized that the contemporary business environment is marked by intense competition, rapid transformations, and intricate challenges. Organizations worldwide, regardless of their size, confront issues such as swift technological advancements, disruptive business models, emerging markets, and stiff competition. To address these hurdles effectively, organizations should contemplate the adoption of Total Quality Management (TQM), a widely recognized concept that has proven beneficial for achieving organizational excellence objectives and enhancing customer satisfaction (Gowthami et al., 2022). Unlike the traditional approach, TQM prioritizes enhancing the efficiency of processes and the capacity to meet customer needs promptly. The implementation of TQM comprises three distinct stages: the preparation stage, planning stage, and execution stage, all of which necessitate the commitment of management, active participation of employees, and other critical factors like training and communication (Kumar and Shanmuganathan, 2019). Organizations should perceive TQM as a long-term journey and continually strategize for their future to realize their vision and goals, as opposed to merely attaining short-term objectives.

i. Case of Study: Burj Khalifa Dubai

A notable case study is the Burj Khalifa in Dubai, soaring to a height of 828 meters, and recognized as the tallest building in the world. This iconic structure serves as a compelling example of Total Quality Management (TQM) implementation within the construction industry (Nyarirangwe and Babatunde, 2019). The construction management team, led by Emaar Properties, embraced a comprehensive TQM approach throughout the project's lifecycle. This approach encompassed activities such as an in-depth analysis of customer requirements, the formulation of a robust quality management plan, the execution of stringent quality assurance procedures, the creation of a communication strategy, and the provision of comprehensive employee training. Additionally, the TQM approach featured an ongoing process of improvement aimed at ensuring customer satisfaction, upholding quality workmanship, and utilizing premium materials and equipment. The successful application of TQM culminated in the timely and within-budget completion of the Burj Khalifa, accompanied by a high level of customer satisfaction (Cherian, 2020).

Figure 7. Burj Khalifa Dubai (Kononenko et. Al., 2022)

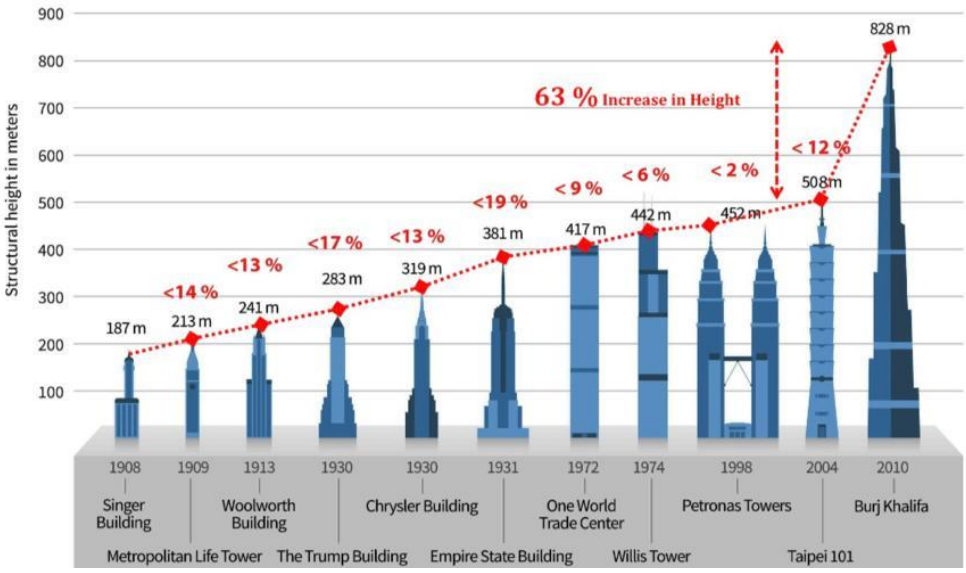

Figure 8. The Burj Khalifa, tallest building in the world (Osama Al-Sehail, 2014)

ii. Benefits

Total Quality Management (TQM) offers numerous advantages to organizations, which encompass heightened customer contentment, superior product and service quality, enhanced operational efficiency, and lowered expenditures (Ramlawati & Putra, 2018). TQM also elevates employee morale, fosters engagement, and forges a competitive edge. The central focus of TQM on continuous enhancement and the involvement of employees in refining quality can lead to elevated performance, augmented profitability, and bolstered customer allegiance.

iii. Challenges

The implementation of TQM can encounter various challenges, including resistance to change, scarcity of resources and expertise, and complexities in assessing success. TQM can inadvertently stifle creativity and innovation by excessively stressing process and procedures. Achieving successful implementation necessitates resolute leadership, adequate resource allocation, and surmounting these obstacles.

iv. Key finding

The incorporation of TQM in the realm of construction yields notable benefits, including the enhancement of project outcomes, the curtailment of wastage, the amplification of efficiency, and the enrichment of customer satisfaction.

4.4. Supply Chain Management

The concept of Supply Chain Management (SCM) involves the intricate integration and coordination of multiple operations and functions related to the flow of information, materials, and finances. This integration is geared towards the efficient and effective design, production, and timely delivery of products to end-users (David-West, 2020). Effective supply chain management plays a pivotal role in ensuring the prompt and efficient delivery of products to end-users. This entails having access to the right data, resources, and quantities necessary for producing the desired product and ensuring that it reaches the correct location in good condition, at the right time, and at an optimal cost. Jagdeep Singh (2019) underscores that this process is indispensable for accurate forecasting and the successful management of the supply chain.

4.4.1. ICT Supported Supply Chain Integration

The increasing complexity of supply chains, driven by rising customer expectations and product demands, has compelled businesses to adopt innovative strategies to remain competitive and operationally efficient (Hussein et al., 2021). To challenge traditional practices, companies are now mandated to incorporate Information and Communication Technology (ICT) tools and platforms across various aspects of the supply chain. These technologies enable organizations to improve their visibility, cut expenses, enhance efficiency, and foster transparency across the entire supply chain. Their functionalities cover aspects like transportation, manufacturing, inventory tracking, and communication among suppliers, manufacturers, distributors, and customers (David-West, 2020).

i. Case of Study: Skanska construction company

Skanska, a prominent global construction company, has successfully adopted a digital system called "Connected Construction" to streamline their management of the supply chain. This system offers a range of functions, such as real-time monitoring of materials and equipment, automated order processing, and digital payment solutions. Through the implementation of this system, Skanska has simplified their supply chain operations, minimized lead times, and improved communication between suppliers and project teams. Furthermore, it has provided a higher level of transparency in their supply chain, facilitating efficient project monitoring and early issue detection. In the end, Skanska's incorporation of information and communication technology (ICT) into their supply chain management is strengthening their competitive edge in the construction sector by increasing efficiency, reducing expenses, and delivering top-quality projects to their clientele.

Figure 9. Skanska construction company (Skanska, 2023)

ii. Benefits

Information and communication technology (ICT) tools offer the capability to enable remote operations, expedite corporate processes, and improve logistical efficiency, as emphasized by David-West (2020). Additionally, they can be harnessed to monitor carrier pickups at regional distribution hubs, facilitating transport coordination, manufacturing management, and the real-time tracking of inventory levels, as pointed out by Craighead et al. (2020).

iii. Challenges

However, the integration of ICT into supply chain management comes with its share of challenges. These include the expenses associated with setting up and maintaining ICT systems and technologies, as well as the potential risks of data security breaches and cyber-attacks (Kumar & Mallipeddi, 2022).

iv. Key finding

The adoption of Information and Communication Technology (ICT) by businesses can yield a variety of benefits within the supply chain. These benefits encompass improved visibility, cost reduction, enhanced efficiency, and increased transparency throughout the supply chain.

4.4.2. Public-Private Partnership

Public-Private Partnership (PPP) is a procurement approach that entails collaboration between the public and private sectors to deliver public infrastructure projects (Cui et al., 2018). This approach, as indicated by Koppenjan et al. (2022), has demonstrated positive impacts on building performance and environmental outcomes.

i. Case of Study: Manchester Civil Justice Centre

A remarkable project achieved through a highly effective partnership between the public and private sectors, completed on schedule and within the budget, is the Manchester Civil Justice Centre. This £160 million collaboration between the government and Allied London encouraged innovation and cooperation across both public and private domains, resulting in more efficient and cost-effective solutions. The design of the building, aimed at reducing energy consumption, water usage, and waste generation, led to a diminished carbon footprint and reduced greenhouse gas emissions. The adoption of the Public-Private Partnership (PPP) approach facilitated a more comprehensive consideration of environmental factors during the design and construction phases.

ii. Benefits

Public-Private Partnerships (PPPs) are frequently commended for their capacity to provide incentives for on-time project completion, a significant advantage over traditional procurement methods, as emphasized by Koppenjan et al. (2022). PPP arrangements can stimulate innovation, contributing to Value for Money through reduced construction timelines, overhead costs, as well as operation and maintenance expenses (Dharmapuri Tirumala et al., 2021). Additionally, PPPs can yield cost savings and offer improved value for money by effectively allocating project risks (Wu et al., 2018).

iii. Challenges

Studies have shown that PPP projects may often demand more time for planning and procurement and potentially involve higher transaction costs (O'SHEA et al., 2018).

iv. Key findings

The adoption of the PPP approach has demonstrated positive effects on building performance and environmental outcomes.

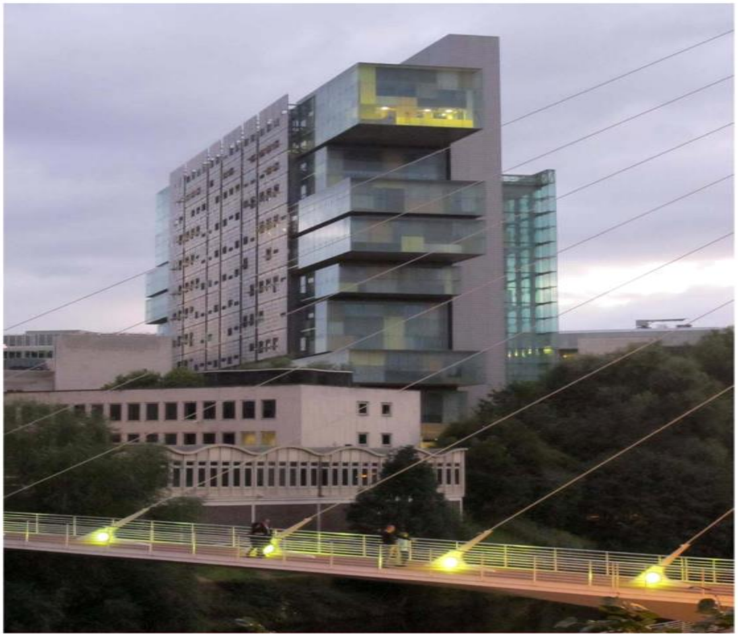

Figure 10. Manchester Civil Justice Centre (Napier, 2013)

5. DISCUSSION

The construction industry is indeed experiencing a significant shift towards sustainability, integrating environmental stewardship, resource efficiency, and societal welfare (Zúñiga-Torres et al., 2021). This transformation is being facilitated by cutting-edge research, innovative materials, and holistic design strategies (Zúñiga-Torres et al., 2021). The adoption of sustainable practices in existing buildings, particularly those owned by the government, is indicative of a commitment to sustainability and fosters an appropriate approach (Hamzah & Hasim, 2018). Furthermore, the momentum for sustainable construction project financing has been significantly accelerated, particularly following the release of the G20 Action Plan on the 2030 Agenda for Sustainable Development ("Sustainable Project Financing and Financial Model: Take Construction Enterprises as An Example", 2022). These developments underscore a paradigm shift in global building practices, emphasizing a more sustainable, resilient, and ethically responsible future (Zúñiga-Torres et al., 2021).

The societal perspective plays a crucial role in driving sustainable construction practices. For instance, societal characteristics and cultural norms influence the use of informal and formal home care among older adults in Europe (Suanet et al., 2011). Moreover, the level of collectivism within a society determines the extent to which an individual's welfare is affected by the rest of the society and vice versa (Ahuja et al., 2014). Additionally, the societal preferences and concerns for farm animal welfare in developed countries reflect the societal influence on sustainability and ecological considerations (Cornish et al., 2016). The transition towards sustainable construction represents a multifaceted endeavor that encompasses technological advancements, societal values, and financial mechanisms. The integration of environmental stewardship, resource efficiency, and societal welfare underscores a paradigm shift in global building practices, paving the way for a more sustainable future.

The multifaceted exploration presented in this study intricately interweaves various facets of sustainable construction, encapsulating a vast tapestry of research and empirical evidence. The synthesized information converges on pivotal themes, ranging from the integration of innovative technologies and materials to the evolution of management paradigms, all aimed at fostering sustainability within the construction industry.

- A significant focus of this synthesis is the integration of environmentally conscious materials and technologies. The literature review elucidates the growing prominence of nano-based materials, such as nano titanium dioxide (Hischier et al., 2017), and their role in enhancing structural integrity while mitigating environmental impact. Furthermore, the discourse delves into the realm of green buildings, echoing studies by Khoshbakht et al. (2018) and Ravindu et al. (2015) that highlight the heightened satisfaction and environmental benefits associated with such constructions.
- The alignment between lean construction methodologies and environmental sustainability emerges as a critical nexus, evidenced by the works of Eltawy and Gallear (2017) on leanness and agility, and Goh and Goh (2019) on simulation-based lean production in modular construction processes. This convergence underscores the industry's pursuit of efficiency, waste reduction, and adaptability, mirroring the global shift towards leaner, more agile operational frameworks.
- The study further navigates through the intricate landscape of Public-Private Partnerships (PPP) in infrastructure development. Comparative analyses by Kumar and Shanmuganathan (2019) and Tolba, Melilla, and Al Nassa (2020) dissect the nuances between traditional modes and PPP, offering insights into their respective strengths and weaknesses, particularly in educational and infrastructural domains. These comparisons serve as a compass guiding stakeholder in making informed decisions while navigating the complexities of infrastructure development.
- Moreover, the study intricately weaves the Sustainable Development Goals (SDGs) into the fabric of corporate social responsibility within construction practices, aligning with Fallah Shayan et al.'s (2022) perspective on integrating SDGs as a framework for CSR. This integration emphasizes the industry's role in aligning with global sustainability objectives while addressing socio-environmental concerns.

The inclusion of case studies; Manchester Civil Justice Centre, New Royal Adelaide Hospital, and The Edge in Amsterdam, offers invaluable insights into sustainable construction practices. However, further refinement in seamlessly integrating these case studies into the narrative is pivotal to bolster the argumentation. Each case study is a testament to distinct facets of sustainable construction, warranting a more explicit delineation of their contributions towards addressing the research questions to enhance overall coherence.

The Manchester Civil Justice Centre exemplifies the profound impact of strategic material selection and energy conservation measures on sustainable construction. Its detailed analysis resonates with the core research focus, illuminating the intricate relationship between material choices and the sustainability spectrum. Conversely, the New Royal Adelaide Hospital's case study accentuates the challenges posed by cutting-edge technological innovations juxtaposed against stringent project timelines. This critical examination provides unique insights into reconciling sustainability mandates with pressing project deadlines. Additionally, The Edge in Amsterdam serves as an exemplary model showcasing the harmonious amalgamation of avant-garde design and operational efficacy. Its emphasis on technological integration underscores the pivotal role of innovation in achieving and surpassing sustainable benchmarks. When interconnected with the primary research questions, these case studies collectively fortify the argument for embracing multifaceted sustainable construction practices.

The synthesis presented in this paper lays a robust foundation for comprehensive discourse within the sustainable construction domain. Its harmonization of diverse perspectives and empirical evidence not only enriches the theoretical framework but also accentuates the practical implications for stakeholders, policymakers, and researchers. However, within this rich tapestry of findings, certain gaps beckon further exploration. The intricate interplay between technology, sustainability, and economic feasibility warrants deeper investigation to unravel the cost-benefit analysis and scalability of integrating cutting-edge innovations into real-world construction scenarios. Collectively, these enlightening case studies offer deep insights into various sustainable practices and technologies that can be embraced by the construction industry. From the utilization of advanced materials and nanotechnology to the exploration of wood innovation, waste management strategies, lean construction principles, total quality management, digital platforms, and public-private collaborations, these examples showcase the incredible potential for creating sustainable, energy-efficient, and environmentally conscious buildings. The challenges highlighted throughout each case study also serve as crucial considerations for industry stakeholders, paving the way for meaningful advancements in sustainable construction practices.

6. CONCLUSION

This study meticulously delves into the imperative role of holistic approaches in nurturing sustainable construction practices. Beyond the facade of green building techniques, it underscores the necessity for comprehensive considerations encompassing environmental, social, and economic facets, aiming for enduring viability and positive impact. The findings unequivocally showcase the multifaceted benefits stemming from a holistic mindset. Projects, through integrated principles like energy efficiency, renewable resource utilization, waste reduction, and community engagement, not only mitigate environmental footprints but also yield substantial social and economic returns.

Furthermore, exploration into advanced technologies and innovative materials unveils promising avenues for sustainable construction. The convergence of technologies like Building Information Modeling (BIM) and the Internet of Things (IoT) empowers stakeholders, enhancing resource management, streamlining processes, and optimizing building performance. Their seamless integration holds immense potential for a transformative shift in the industry toward sustainability and resilience. Yet, acknowledging challenges in widespread adoption is crucial. Overcoming these hurdles demands heightened awareness, supportive policies, and transformative mindsets. Collaboration among governments, industry experts, research institutions, and local communities is pivotal in driving tangible change. In essence, the trajectory toward sustainable construction mandates a collective commitment to holistic approaches. By assimilating insights from real-world projects, we pave the way for a built environment harmonizing with nature, fostering equity, and ensuring long-term prosperity.

7. LIMITATION

While the case studies conducted in this study provide valuable insights into the subject matter, it is important to acknowledge their limitations. The following limitations should be taken into consideration when interpreting the findings and conclusions:

a. Generalizability: The findings and conclusions drawn from the studies may not be generalizable to broader populations or contexts. Each case study represents a specific situation, and the results may be influenced by unique circumstances, making it challenging to apply the findings universally.
b. Selection Bias: The selection of case studies may introduce a bias, as they were chosen based on specific criteria or availability. The chosen cases might not represent the entire range of possibilities, limiting the diversity and generalizability of the findings.
c. Time Constraints: The studies were conducted within a certain timeframe, which may have imposed limitations on the depth and scope of the research. It is possible that certain aspects or factors relevant to the subject were not fully explored or could not be adequately covered within the given time limitations.
d. Subjective Interpretation: The interpretation of the study data relies on the subjective judgment of the authors. Different analysts may interpret the information differently, leading to potential variations in the conclusions drawn from the case studies.
e. Lack of Control: As case studies involve real-world situations, we have limited control over external variables that could have influenced the outcomes, for example environmental conditions, and organizational dynamics.

By acknowledging these limitations, future research can address these gaps and provide a more nuanced and comprehensive analysis of the sustainable construction practices.

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