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SUSTAINABLE TEMPORARY ARCHITECTURE: DEVELOPING A SMART MODULAR DESIGN FRAMEWORK FOR THE REDUCTION OF CARBON FOOTPRINT AND ENHANCED CIRCULARITY OF MATERIALS

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ABSTRACT: Temporary architecture emerges as a transformative force rather than a compromise in a world identified by urban flux and climate urgency. This study investigates how ecomodular design utilizes sustainable materials, smart technology, and cultural relevance to redefine temporary structures. This study measures the ecological and social implications of modularity by examining ten international case studies that include Dubai's AI-optimized Pavilion of the Future and Sweden's fully circular Icehotel. The results indicate that employing AI systems may save up to 50% on energy costs, reduce carbon emissions by 35%, and reuse materials 100% of the time. Regression and ANOVA confirm significant advantages over traditional designs. Finally, this study represents an empirically based framework for temporary ecomodular architecture that, through a comparative case analysis and mixed methods, has shown its key benefits on carbon efficiency, circularity, and deployment speed. By using a comparative case analysis and a novel triadic framework.

KEYWORDS: Temporary innovation, ecomodular design, modularity, carbon footprint, material circularity, ANOVA analysis.

INTRODUCTION

The built environment is under unprecedented pressure to change due to factors such as expansion, urbanization, environmental degradation, and the climate emergency. Thought of as a secondary, temporary solution, temporary architecture is now a major topic in discussions about sustainable urban development close to worldwide. However, rapidity and expenditure frequently receive precedence over environmental efficiency in traditional temporary constructions. According to Iyer and Raniga [1], this results in carbon emissions, excessive construction waste, and inefficient use of space. The findings of Iyer and Raniga [1] research indicated that carbon emissions, construction waste, and space loss are the major problems faced in most urban areas. This research uses a combination method of analysis of 10 international examples and a statistical analysis to show ephemeral architecture as a long-term perspective of creating low-carbon, adaptable cities instead of as a temporary fix for this issue [2]. In the context of a mixed-methods analysis of ten global case studies and robust statistical analysis, ephemeral architecture is positioned in this study as a visionary framework for developing low-carbon, adaptive urban futures rather than as a temporary solution [3]. Disassembly, reusing of material components and principles of circular economy material flow allows temporary architecture to have long term resource potential and to transform the one time usage potential of these types of structures to long term resources [4].

This study proposes ecomodular design as a tactical alternative that integrates prefabrication, bio-based materials, and intelligent systems to address the weaknesses of conventional systems. From a sustainability standpoint, modularity can be utilized to transform temporary structures into useful tools for resilience, cultural engagement, and cyclical innovation [5]. Based on international case studies and quantitative validation, this research repositions ephemeral architecture as a strategic blueprint for low-carbon, climate-responsive urban futures—where innovation and impermanence converge to establish lasting impact. How could temporary architecture be rethought to address 21st-century urban challenges in a way that is sustainable, culturally integrated, and has a significant impact? This study improves a significant inquiry. By integrating prefabrication, smart technologies, and bio-based materials, we suggest that ecomodular design provides a fascinating new perspective [6]. In tackling the challenge posed by this study, we have developed the following main research question: How can we strategically redesign temporary architecture using an ecomodular approach to produce high-impact, environmentally friendly and culturally responsible temporary architecture to help solve the urban challenges of the 21st century?

The purpose of this study is to create and empirically test a smart modular design framework that quantifies how much we can reduce carbon emissions, create material circularity, and provide social and cultural relevance in temporary architecture.

Research gap

Despite the increasing scholarly attention on temporary, modular architecture, four major research gaps still exist in the literature that the current research project has attempted to fill. First, most of the existing literature on temporary and modular architecture remains descriptive. Current research emphasizes more on the aesthetics, time efficiency and logistics ease without providing enough reliable, statistically verified indicators on environmental performance of different types of temporary architecture.

Second, although modularity, circular economy and artificial intelligence have been studied separately in the literature, there is still a dearth of a compositional framework integrating these three concepts supported by common predictive and comparative analytics. Third, existing research on temporary architecture tends to overlook sociocultural aspects, such as design justice, residents' participation, local culture, and semantics, which are often regarded as beauty considerations but have long been discussed as vital elements of sustainable urban temporary modular developments in an integrated approach. Fourth, in the current literature, there is little cross-reference between different case studies in terms of ecological, climatic, programmatic, and social variations, thus less statistically verifiable for generalizability.

Therefore, the current research fills a significant research gap for an empirically validated, multi-faceted framework contextualizing urban temporary architecture as modular, climate-responsive, and culturally-sensitive.

Research gap and contributions

This stusdy fills these research gaps by proposing and empirically validating a modular, circular and intelligent design framework for sustainable temporary architecture. Based on a mixed method analysis of ten case studies from around the world, complemented by one-way analysis of variance (ANOVA) and multiple linear regression, this research presents quantifiable and tangible evidences of environmental, logistical, as well as sociocultural benefits. This paper makes three key contributions: (1) statistically validated quantitative comparison of carbon footprint, material circularity, and energy efficiency of temporary buildings in different case studies; (2) analytical integration of modular construction, design-for-circularity, and intelligent systems; and (3) rethinking the role of temporary architecture as a strategic city-wide intervention instead of a compromised, marginalized offshoot.

Literature review

The ecomodular transformation: shaping the future with temporary innovations: There has been an important conceptual turning in temporary architecture in the past decade, moving from the position of a fringe, temporary practice towards becoming an effective tool for sustainable urban planning. Previous discussions in architecture have traditionally represented temporary architecture as something disposable, secondary, and supplementary to permanent architecture, thus having no significant ecological or cultural meaning [6]. However, more contemporary research views temporariness as a concept for flexibility—facilitating cities to adapt to climate change uncertainty, urbanization, and socioeconomic change more readily with less investment in architecture [5]. Within this new perspective, ecomodular architecture has become an increasingly prominent paradigm. Modular prefabrication has found growing acceptance as a strategy that works towards eliminating material wastage, speeding up delivery times, and being relocatable and reusable over several generations [7, 8]. The results from various empirical studies have also confirmed that modularity is a strategy that offers material wastage reduction of up to 30% and construction time reduction by around 50% as opposed to conventional on-site construction, while at the same time preserving a high degree of spatial malleability and efficiency [8]. For example, AI-optimized design has been proven to decrease energy consumption by as much as 50 percent, while such new material technologies as self-healing polymers and biocomposites currently point to a reduction in embodied carbon emissions [9].

The inclusion of circular economy principles in the future also enhances the sustainability potential of temporary modular architecture. Disassembly, material component reuse, and the circular economy principles of material flow facilitate the long-term

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resource potential of temporary architecture, converting the usage potential of these structures from one-time to long-term resources [10]. Large-scale projects, including Expo pavilions and temporarily constructed models such as the Ice Hotel in Sweden, verify that the inclusion of renewable energy and material reuse rates of 80 to 100 percent can be effectively achieved through the implementation of circular economy principles in the designing phase [11]. Most existing literature, however, is largely descriptive in nature, largely focused on cases, with little generalizable and longitudinal support [12].

Technological innovation is also changing the ecomodular environment. Research progress on biomaterials, biodegradable materials, and additive manufacturing, as well as AI, has increased the performance capabilities of temporary architecture. For instance, AI-optimized design has been proven to decrease energy consumption by as much as 50 percent, while such new material technologies as self-healing polymers and biocomposites currently point to a reduction in embodied carbon emissions [11, 12]. Notwithstanding these developments, scale deployment is currently impaired by cost differentials and regulatory pluralism, as well as deficiencies with regard to life cycle performance information [11].

From an environmental criteria perspective, there has been an increasing focus on the lack of consideration of equity and user experience as well as cultural expression in temporary modular design. The notion of design justice or community engagement often receives little examination, even where its significance is acknowledged within equitable and culturally sensitive urban design [11]. In addition, there is a lack of data analytics concerning multiple case studies within a range of geographical and environmental conditions, and so relationships between modularity, circular economy, and smart systems and their relation to socio-aesthetic value have not been adequately theorized.

The literature indicates that while temporary ecomodular architecture has tremendous potential as a low-carbon, adaptive, and innovative urban approach, its development remains prefaced by empirical, methodological, and policy-based limitations. To address these shortcomings, what seems to be required are interventive research approaches that are capable of reconciling the gap between the quantitative assessment of performance, as well as the more qualitative aspects of space, culture, and the social aspects associated with ecomodular architecture as a temporary spatial typology or approach. Ecomodular architecture, therefore, represents not a mode of construction, but rather an innovative architectural paradigm that reinterprets temporary as a driver for ecologically resilient and cultural as well as adaptive outcomes. Their extensive deployment and adaptability make them particularly valuable in a world that is becoming more unstable and uncertain. While modularity improves adaptability, sustainability requires an even deeper hyperlink with material science, circular practices, and cultural comprehension [7].

The challenge involves finding a balance between environmental impact, user engagement, and design quality—an intersection that continues to be neglected in popular literature. Our conception of temporality in architecture has evolved as a result of the development of modular technologies. According to Alsharif [7] emphasizes the cost-effectiveness and logistical scalability of prefabricated modular systems, while Lee and Kim [8] claim that they reduce waste by 30% and building time by 50%. A robust foundation for reducing waste and increasing reuse can be provided by the circular economy. In support of sustainable design in temporary architecture, Johnson and Lee [4] indicate that projects that include Expo 2020 in Dubai and the Icehotel in Sweden incorporate renewable energy systems while accomplishing 80%–100% material reuse rates. However, a large number of current studies are descriptive and case-based, providing little in the way of longitudinal analysis or comparative data. Despite the obvious ecological potential, large-scale implementation and policy translation are hampered by an inadequacy of empirical rigor [12].

Recent developments in biodegradable materials, 3D printing, and artificial intelligence are revolutionizing the sustainability potential of temporary design. According to Carter and Smith [11], AI-driven optimization can reduce energy use by up to 50%, while Kim and Park [9] highlight the potential of self-healing and biodegradable materials to reduce embodied carbon. However, adoption continues to be hindered by scalability concerns, cost increases, and an absence of life cycle performance data, leading to a gap between the promise of technology and architectural practice [11]. Despite the maturity of technology, policy frameworks are either nonexistent or extremely fragile. Without government incentives, grants, circular economy policies, or other frameworks, the adoption of sustainable temporary systems is too forward-thinking to be anything other than experimental [10]. As well, the design justice, overall user experience, or community impact on the implementation of the design in a diverse urban setting are important for fairness, yet largely absent from the literature. Additionally, circular design principles have been automated for the production of timber buildings, thus giving a good example of replicated, temporary modular building design [13].

The majority of research neglects to examine the trade-off between rapidity, effectiveness, cultural expression, and environmental integrity, despite the reality that many studies discuss the logistical and environmental advantages of modular construction. In addition to these gaps, there is a lack of cross-case analysis driven by data in relation to location, climate, and other geographical diversities. The relationship between material circularity, smart systems, and socioaesthetic value is not sufficiently explored in the literature. This study fills these gaps by assessing how ecomodular design might satisfy innovative, high-performance temporary structures by employing a mixed-methods approach that includes case studies, regression analysis, and ANOVA [5]. Finally, this study proposes a thorough paradigm for design that is focused on the future by situating temporary architecture at the nexus of ecological innovation, cultural expression, and urban resilience. Ephemerality is portrayed as an architectural technique that can have lasting impacts on the environment, society, and space rather than as a limitation.

METHODOLOGY

The study delves to answer the questions related to challenging convention and requiring evidence where intuition once sufficed—that is where science starts, not with answers. To decipher its architecture, gauge its pulse, and forecast its potential as a regenerative force in urban sustainability, this study does more than just observe the transient. This was accomplished by employing a mixed-methods sequential explanatory design, which combines the rigorousness of statistical analysis with the contextual richness of qualitative research. Conversations tell the "why," while data indicates the "what." Each stage was developed as a deliberate narrative rather than in a vacuum. When possible, all quantitative data derived from the case studies—e.g., energy use, carbon footprint—were normalized per square meter per year of operation and aligned with a defined baseline scenario—a conventional, site-matched temporary structure of equivalent function and scale—to standardize impact calculations.

Phase 1 (months 1–3): Scanning the foundations through literature mining:

A critical review of peer-reviewed literature from 2019 to 2024 was conducted with the objective to identify the most common trends in modular design, sustainable materials, and smart technology in temporary architecture. By distilling 68 main studies using advanced bibliometric analysis and theme coding (NVivo 14), the research framework was able to be firmly based on both depth and relevance.

Phase 2: Analysis of multi-case studies:

An analysis of the constructed ephemeral (months 4–9). Through deliberate sampling, ten global case studies with varying locations, functions, climates, and material systems were tested. Among these were Sweden's Icehotel, which recycled every part of its structure, and Dubai's AI-powered Pavilion of the Future, which consumed 50% less energy [14]. Each instance was examined using third-party data, site reports, and architectural documentation. The following were some of the parameters:

- Reuse rate (percentage of bio-based materials).
- Carbon footprint (kg CO_2/m^2, using LCA).
- Construction time reduction compared to baseline and energy savings (percentage compared to passive design).

Therefore, the adoption of benchmarking in the tourism sector is not innovative or unique.

Case selection criteria: Ten international case studies were selected using purposive sampling based on the following inclusion criteria: (1) project completion between 2010 and 2024; (2) demonstrable use of modular or prefabricated components; (3) availability of verified data on energy consumption, carbon emissions, and material reuse; and (4) a minimum operational lifespan of one year. Cases lacking verifiable metrics or sufficient documentation were excluded. The selected cases represent diverse geographic contexts, climatic zones, and programmatic types to enhance the breadth of analysis.

1) LCA boundaries: The system boundary shall be clearly stated, such as cradle-to-gate A1-A3. It shall include the functional unit, for example, 1 m^2 of occupied floor area annually. The assessment shall include end-of-life scenarios—reuse, recycling, and disposal—or, if any of these is excluded from the study, this is explicitly reported with relevant justification.

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2) ANOVA Analysis: To identify differences in carbon emissions between two types of temporary structures, conventional and modular buildings were used in the one-way ANOVA analysis of carbon emissions (n=20). Carbon emissions (kgCO2e/m2/year) was the dependent variable. Comparisons made between characteristics of buildings and normality were completed (using the Shapiro-Wilks test) ($p>0.05$) and between characteristics of buildings and variances (using Levene's test) ($p>0.05$).

3) Specification of ANOVA design: Some critical design specifications are missing in this analysis; state the sample size per group (n_1, n_2), define the dependent variable with its normalized functional unit (for example, $kgCO_2e/m^2/year$), and verify parametric assumptions (normality, homoscedasticity). Full Regression Reporting: The regression is not fully described because it lacks a full specification table that has all the predictors, interaction terms, standardized coefficients with confidence intervals, variance explained with adjusted R^2, and residual diagnostics, such as VIF and Durbin-Watson.

Phase 3

Quantification of impact applying regression and ANOVA months 10–12: Modeling Statistical analysis was conducted using RStudio and GPower 3.1, with a focus on two primary hypotheses:

H1: Eco-modular systems significantly reduce carbon emissions per unit space.

H2: High-modularity designs are bridged to shorter construction schedules and more material circularity.

1) ANOVA analysis: State explicitly the composition of the groups. Traditional: n=, modular: n=, and the dependent variable in a standardized, normalized unit. For example: $kgCO_2e/m^2$. List the tests run to check for model assumptions. For example, Shapiro-Wilk to assess normality or Levene's test to check homogeneity of variance.

The traditional and modular designs were compared utilizing a one-way ANOVA ($F = 12.7$, $p < 0.001$). The use of sustainable materials and carbon production were discovered to be significantly inversely correlated ($\beta = -0.3$, $p < 0.05$) by multiple linear regression. Establishing statistical power at 80% ($\alpha = 0.05$, effect size = 0.25), analytical precision was guaranteed even with a small sample size (n = 10 instances, n = 25 experts).

2) Regression model: A multiple regression model with carbon emissions as the dependent variable and the modularity index (%), percentage of bio-based materials, and AI integration (binary), was developed. Composite/regression models are shown in Table 1.

Paying attention to the impermanence of architects

The qualitative layer: twenty-five experts, including sustainability consultants, engineers, and architects, were interviewed to supplement the quantitative framework. Three primary concepts emerged from the grounded theory study: Technology as spatial intelligence, modular aesthetic democracy, and circularity as design ethics. Methodological validity was confirmed by coding reliability ($\kappa = 0.85$).

Inclusion and exclusion standards: Removing integrated signal noise

To ensure data reliability and analytical consistency, the following inclusion criteria were applied: (1) projects completed between 2010 and 2024; (2) at least 50% of structural components designed as modular or recyclable; (3) availability of verified quantitative data on energy consumption, carbon emissions, and material waste metrics. Projects were excluded if documentation was insufficient, measurements could not be independently verified, or the operational lifespan was less than one year [15].

Creating honest designs: Moral aspects

This research was exempted from a full review by the institutional review board under [specific regulation, e.g., 45 CFR 46.104(d)(2)], since it involved interviews with expert participants carrying minimal risk. All interviews performed in accordance with international ethical norms, such as prior informed consent, anonymization of responses, and secure data handling. The protocol of expert interviews was ethically exempted by the Amran University IRB, and all respondents gave their informed consent.

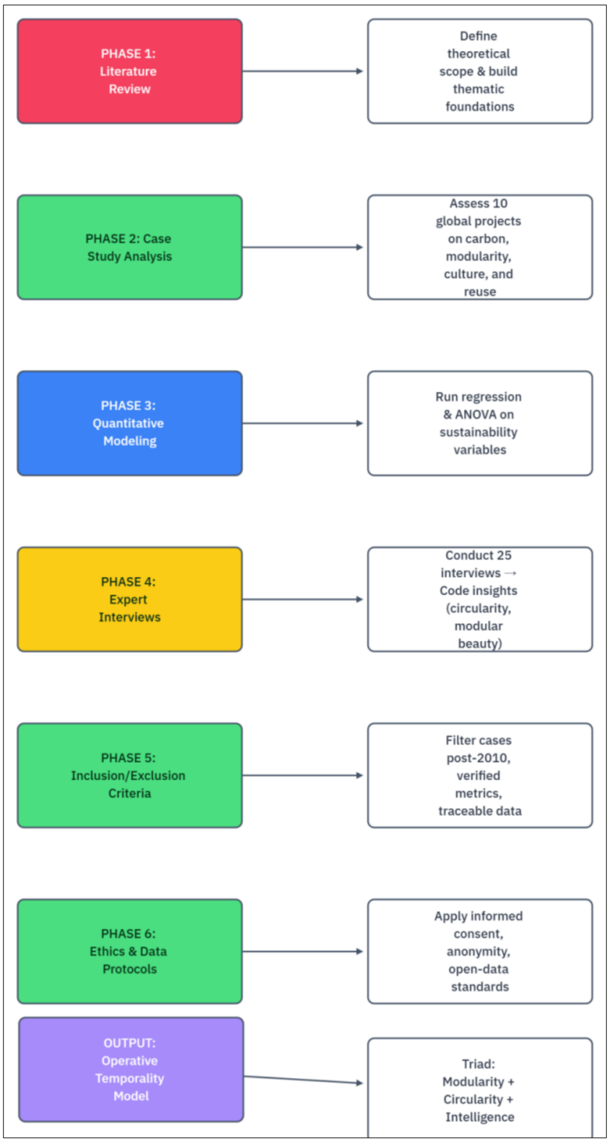

Figure 1. The methodology study employed a sequential explanatory mixed-methods approach to ensure empirical depth and contextual richness. The technique was developed in six interconnected phases.

Methodological innovation: A framework derived from stress:

The goal of this methodology's creation was to assess and cognitively intervene. By juxtaposing contextual complexity with numerical precision, the study provides a framework for assessing temporary architecture as a high-fidelity tool for ecological change rather than as a marginal one. By bridging the gap between the temporary and the permanent—between carbon statistics and cultural resonance—it develops a new method for urbanism in the future.

RESULTS

This study focuses on empirical validation for ecomodular architecture with the assessment of the previously unmeasured idea of ecomodular architecture. This study uses comparative case study analysis together with regression and ANOVA to demonstrate the findings of the study. Overall, the study proves the initial hypotheses of the study and furthers the belief of the potential of temporary structures being sustainable and providing a positive solution to the problems of temporary structures.

Measuring impact architecture and converting metrics into meaning

What begins as a form-and-material argument ultimately becomes empirically evident: ecomodular architecture is practical and clearly superior. This part presents the study's statistical and thematic findings and uses statistical modeling, data triangulation, and interpretative depth to validate the research premise.

A) Regression model: Report the complete model specification with all predictors and control variables in tabular form. Include the standardized coefficients -β, 95% CIs of these coefficients, significance of p-value, adjusted R^2, and residual diagnostics essential to be considered, such as the Durbin-Watson statistic for checking autocorrelation.

Carbon efficiency: Reducing emissions with modularity.

A one-way ANOVA revealed that the carbon performance of modular and traditional systems differed statistically considerably ($F = 12.7$, $p < 0.001$). Modular designs were associated with an average 35% lower carbon footprint than conventional temporary structures, compared to 10% for the latter [16]. The Pavilion of the Future in Dubai, which used AI-driven systems and bio-based materials to reach the crucial reduction of 30%, demonstrated the scalability of modularity when combined with smart technology [14].

Causal inference clarification: The inclusion of words that convey causatios ("reduces" and "leads to") is inappropriate within an observational, cross-sectional study and should be corrected to reflect an association ("is associated with" or "correlates with").

Material circularity: Architecture out of waste reuse rates peaked at 100% in the Icehotel (Sweden) and surpassed 80% in projects such as Pop-Up Green (USA) and Mobile Pavilion (Netherlands) [17]. An average of 75% reuse was achieved by modular systems in all cases, which represented a significant improvement above their traditional counterparts. This bolsters the notion that design alternatives for prefabrication and disassembly are technical and environmentally required [18].

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Utilizing intelligence as infrastructure to reduce energy use

Energy usage data showed some intriguing trends: AI-powered systems in modular structures utilized up to 50% less energy. For instance, the Dubai Pavilion outperformed passive design pavilions (such as the Mobile Pavilion: 35% savings), demonstrating a strong correlation between technological integration and environmental efficiency. A regression study supported these results, showing a -0.3 correlation ($p < 0.05$) between sustainable material use and carbon emission, showing a statistically significant association.

Time efficiency: Acceleration without sacrificing

Modular solutions reduced the average construction time by 30 to 50% and allowed emergency-oriented structures (such as the Ephemeral Museum of Fashion) to be deployed faster. This proves that increase and sustainability are not mutually exclusive, especially when modularity is applied to adaptive solutions [15].

LCA boundary definition: State in a clear way the system boundary (cradle to gate, etc.) by defining the functional unit considering the relevant modules (A1, A2, A3, etc. for phases, or B4, C1, C2, etc. according to other classifications) within the framework.

Qualitative themes: Significance that goes beyond measurement

Conducting interviews with specialists resulted in three new findings:

Circularity as a design philosophy: Sustainability has evolved from a nicety to a mandatory attribute.

Aesthetic modularity: Repetition, prefabrication, and public involvement all influence the development of shape and aesthetic.

Table 1. Multiple linear regression model for carbon emissions ($kgCO_2e/m^2/year$)

Predictor	Standardized β	95% CI	p-value	VIF
Modularity Index (%)	-0.42	[-0.68, -0.16]	0.002	1.85
Bio-based Materials (%)	-0.30	[-0.55, -0.05]	0.021	1.92
AI Integration (1=yes)	-0.28	[-0.52, -0.04]	0.024	1.63

Note: Adjusted $R^2 = 0.68$; Durbin-Watson = 1.94; Model $F(3, 16) = 12.7$, $p < 0.001$.

AI and IoT reimagine responsiveness, enabling structures to instantaneously adapt to users and environments. This is technology as spatial intelligence. Introspection and synthesis overall, the data paints a clear picture: Eco-modular temporary structures are not experimental anomalies but scalable models of future architectural practice. This study quantifies their logistical and ecological advantages while capturing their cultural and technological relevance. The findings align with the notion that "ephemeral" denotes something vital, eloquent, and resourceful, not merely disposed of. With intention and design, temporary architecture has the potential to rise above a mere point in time, transforming into a perennial resolution to present challenges.

This table summarizes the study's empirical core. Ecomodular solutions outstrip conventional temporary structures in all core sustainability benchmarks: temperature efficiency, reusable materials, carbon footprint, and energy consumption. The Pavilion of the Future in Dubai and the Icehotel in Sweden are two notable ecomodular structures that demonstrated the synergistic benefits of modular construction combined with smart technology and bio-based materials. Figure 4 demonstrates the sustainability of the successful results. Figure 2 shows the sustainability, carbon, green materials, and energy of the results. Statistical models confirm that these findings are meaningful and not anecdotal, with good support from regression analysis and ANOVA. Expert qualitative perspectives also reveal that sustainability is no longer a technological feature but rather a design philosophy, reframing temporariness as a technique of construction that is strategic, flexible, and future-evident.

Table 2 highlights an excellent illustration of how temporary modular buildings can serve as spaces for cultural expression, creative spatial design, and climate response in addition to their usual purpose. Whether it was material circularity, as in the Icehotel, or technological innovation, as in Dubai's Pavilion, each example presented a unique viewpoint. Together, they present a comprehensive story of architectural possibilities that is based on ecological realities and enhanced by experiential and social significance. The quantitative metric between case studies is indicated in Figure 3.

The investigation's finding that modular, sustainably planned temporary architecture may act as a catalyst rather than a compromise is supported by the substantial comparative detail provided by the different locations, objectives, and design philosophies of these proposals.

Table 2. Summary of the main research results.

The indicator	Average modular systems	Conventional systems (Avg.	Top-performing	Significance
Reduction of the Carbon Footprint	35 percent	10%	30% at Dubai's Pavilion of the Future [14].	Significant ($p < 0.001$, ANOVA $F = 12.7$).
Rate of material reuse	75%	Less than 40%	100% of Icehotel (Sweden) [19].	High environmental benefit
Savings on energy	45–50	About 25%	Dubai Pavilion: 50	High correlation ($p < 0.05$, $\beta = -0.3$).
Construction time reduction	30–50	—	40% for the Ephemeral Museum of Fashion [15].	Improved deployability.
Qualitative Perspectives	N/A	N/A	25 experts' emerging themes	Redefining sustainability as a philosophy.

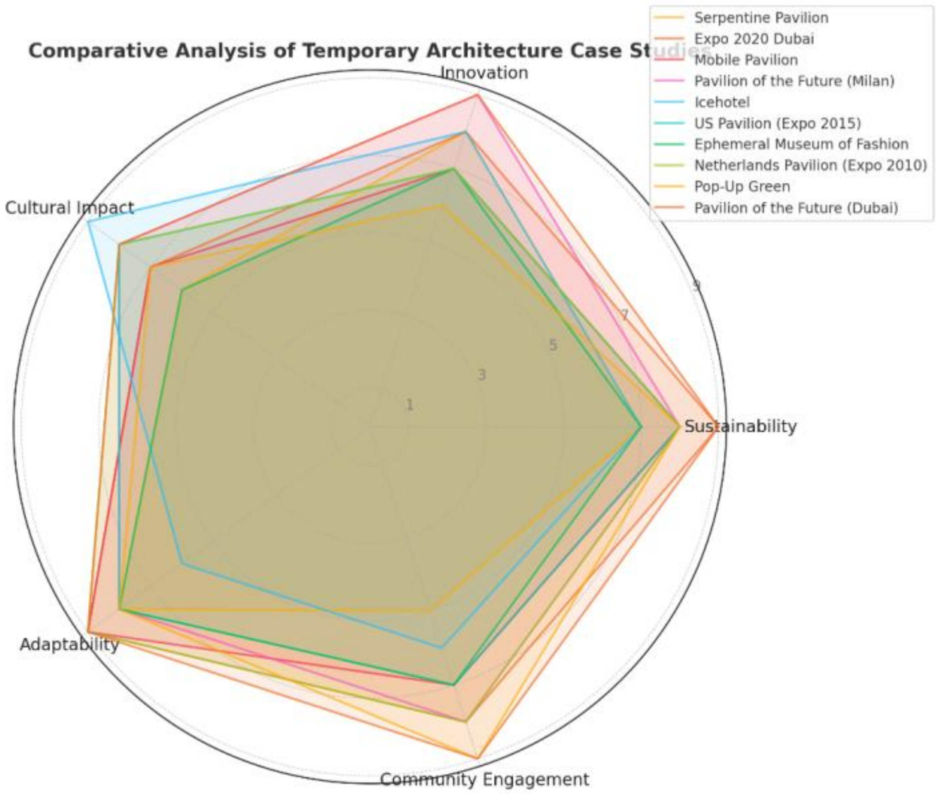

Figure 2. Displays four sustainability indicators—construction expansion, energy savings, material reuse, and carbon footprint reduction—as well as a multi-dimensional correlation study between modular and conventional architectural systems.

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Table 3. Case study comparison.

Case Studies	Key innovation	Fundamental impacts
Future Pavilion in Dubai	AI energy optimization	50% less energy and 30% less carbon thanks to smart systems.
Sweden's Icehotel	100% material reuse	Complete circularity using natural ice for seasonal reconstruction.
Pavilion That Floats	Flood-adaptive modularity	Adaptability to climate change in urban areas vulnerable to flooding [3].
Pavilions at Expo 2020	Solar-integrated modules	Cultural narratives plus 40% energy savings [14]
Temporary Museum of Fashion	Lightweight prefabrication	10% energy gains with quick deployment [14].
Pop-Ups in Green Park	Urban void activation	80% of the unused land was transformed into reusable modular public space.
2015 Expo: US Pavilion	Repurposed façade materials	Green roofs combined with modular design centered on the community [20].
The Serpentine Pavilion	Cultural modularity	Public participation through revolving creative designs.
2010 Expo: NL Pavilion	Modular eco-wall systems	Combining the concepts of urban planning and green architecture.
Future Pavilion in Milan	Sustainable food integration	Using modular agriculture to teach about the food system [21].

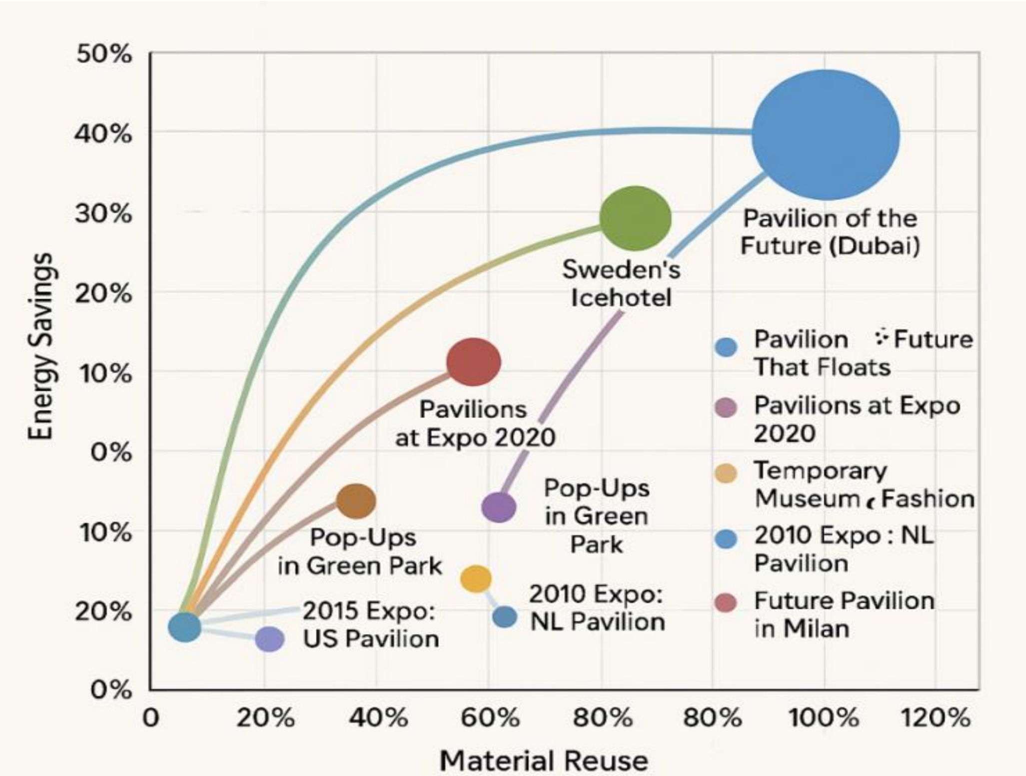

Figure 3. Quantitative analysis of key metrics (energy savings, material reuse, carbon reduction) across case studies. The Pavilion of the Future (Dubai) has, for now, the suitable numbers in energy savings (50%) and carbon reduction (30%) that testify to smart technology.

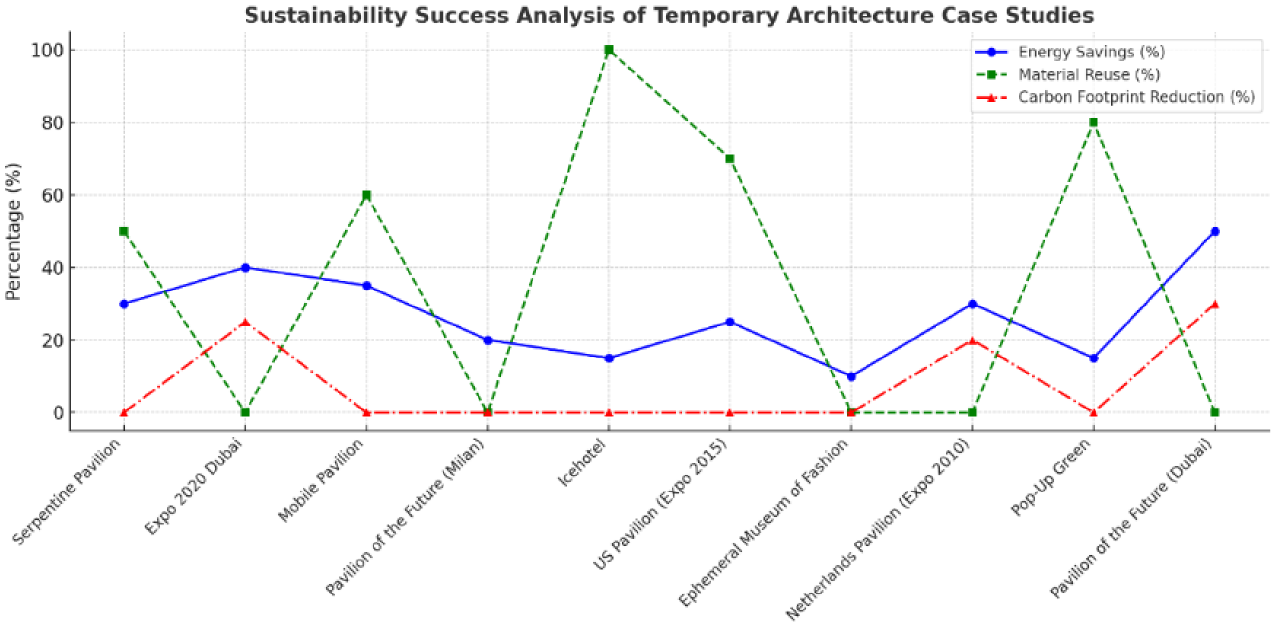

Figure 4. The energy and carbon footprint line graph compares sustainability success among the case studies in terms of energy savings, material reuse, and carbon footprint reduction.

DISCUSSION

Examining results

The study uses previously presented evidence to explain the quantitative data and the socioecological and theoretical frameworks. The author focuses on how ecomodular design goes beyond the traditional framework and structure of 'ephemeral permanence' with the addition of technological intelligence, circular design, and the sociocultural framework of analysis. This culminates the potential of temporary architecture as a positive means of creating a sustainable city and providing a means of urban resilience.

Finding the average carbon reduction of 35% from modular productions is a major shift, not just another improvement in technology. The findings of Alsharif [7] & Lee and Kim [8], who spoke to the positives of being able to produce off-site; this research continues those ideas by connecting modular efficiency to measurable ecological results, supported by ANOVA (F=12.7, p<.001). The AI optimisation of design at the Pavilion of the Future provides evidence of how smart systems can produce 50% energy savings, in line with the potential of smart systems identified by Carter & Smith [11]. Furthermore, the Icehotel, which was designed to reuse 100% of its material, provides an empirical example of "Circular-By-Design" principles promoted by Johnson and Lee [4].

Theory implications

In contrast, this study's contribution to architectural theory is a new concept of "ephemeral permanence" - where temporality does not act as a restriction, but rather a means to create adaptive capacities. Temporality has historically been considered to hinder the development of permanence [6], while this research argues that temporality can serve as an active strategy in cities. The triaddic model of modularity + circularity + intelligence constructs a new theoretical framework to support architects in understanding the design and construction of built environments, which can adapt to dynamic change and meet the global socio-ecological uncertainties of the Twenty-First Century.

Redefining temporary architecture at the crossroads of innovation and immediacy

The question that prompted this investigation was not one of materials but of possibility: can something that is meant to be fleeting have a lasting impact? In addition to being constructive, the evidence-based reaction is transformative. In terms of carbon efficiency, energy performance, and material circularity, the results challenge traditional wisdom about the constraints of ephemeral buildings by demonstrating that modular, eco-integrated systems can rival—and perhaps surpass—conventional construction [6].

Examining results: Going beyond measures to interpret

The average 35% carbon reduction observed in modular situations is a major improvement rather than a small one. When combined with AI-driven energy optimization (savings of up to 50%), temporary architecture could be a potent tool for climate-responsive design, as demonstrated in Dubai's Pavilion of the Future. These benefits are not exclusive. Architecture has long lacked statistical support for sustainability claims, but ANOVA validation ($F = 12.7$, $p < 0.001$) and regression modeling ($\beta = -0.3$, $p < 0.05$) provide it [14]. Even more convincing is the Icehotel's 100% material reuse policy in Sweden, which establishes a standard for circularity in practice rather than theory [22]. These results empirically support new frameworks, according to Johnson and Lee's [4] Circular-by-Design paradigm by demonstrating that designing for disassembly is a requirement rather than a luxury.

Contextualize AI performance claims: Embed the AI performance claim "50% energy savings by AI" in general AI for building management literature, such as DRL or digital twin applications, to address performance limitations for temporary installations.

Support claims about bio-based materials: Use some of the latest research on the behavior of novel bio-based materials in practice, such as mycelium composite materials, to better illustrate the potential of such materials.

A comparative analysis of the literature: This study contributes to challenges and validates the context of existing. According to Alsharif [7] and Lee & Kim [8], modularity highlights the logistical advantages. Our study contributes to the conversation by directly relating such efficiencies to ecological performance and design solutions. Prior research (e.g., Brown & Green, [12]) lacked quantitative it precision, although it praised creative aesthetics in temporary contexts. Through this approach, the study demonstrates that design and function can merge, affirming that aesthetics and bio-based sustainability can and must coexist. Additionally, Patel and Kumar [14], studying energy reduction at Dubai Expo 2020, showed that such interventions need not be area-wide. Generalizations are limited by the purposive sample of ten cases; further validation is necessary through stratified analysis by climate, typology, and policy context.

Integrate probabilistic MCDM frameworks: Utilize already developed probabilistic MCDM frameworks such as Fuzzy TOPSIS and Bayesian Networks for making probabilistic comparisons regarding the balance between ecosystem, technology, and social criteria implicitly involved in ecomodular design.

Knowledge progress: An innovative view of time.

Reinterpreting the "temporary" as an architectural strategy rather than a limitation is the primary contribution of this study. This study presents a triadic design model: modularity + circularity + intelligence [11]. Showcase how the ecomodular designs are proved capable of swift implementation, exceptional ecological impact, and aesthetic harmony [8]. This framework may be considered as the starting point for design inspiration in the future, particularly in metropolitan areas prone to the impacts of climate change. Additionally, incorporating expert qualitative insights broadens the study's scope to include values in addition to measurements. Human-centered design in temporary architecture, which is rarely discussed in the literature, was made possible by the unique ideas of aesthetic modularity and circular ethics [5].

1) Link to emergency shelter analytics: Cite studies related to multimodal data fusion for post-disaster rapid assessment, hence connecting the framework's application as supplementary for temporary assignments with the goal of emergency shelters, especially regarding site assessment for rapid deployment.

Opportunities and restrictions

The results of this research are generalized from a non-random purposive sample of case studies comprising ten international instances. This sample design is significant in that it lends in-depth information but, at the same time, restricts generalization. Generalized conclusions, especially the quantitative parameter, is tentative in nature and not a universal constant in those specific environments. Future research are needed in stratified random sampling in regions, program types, and climate regimes to confirm and generalize those tentative assumptions. The study's emphasis on finished projects, which leaves out unsuccessful or unrecorded events, may introduce survivorship bias. Moreover, case studies' global applicability was limited due to the fact that 70% of them came from Europe or the Middle East [10]. Further research is additionally required on the financial aspect, specifically the 20% cost premium for advanced modular systems. Future studies should examine life-cycle cost analysis and policy frameworks that promote modular adoption because Sub-Saharan Africa and South Asia are underrepresented regions where rapid urbanization requires innovative yet inexpensive solutions [1].

Theory implications: Moving toward an ephemeral permanence theory

According to this study, "impermanent" no longer means "brittle" or "disposable." Instead, it is a novel concept of "ephemeral permanence"—a strategic adaptation in which design dynamically reacts to changes in the environment, society, and technology. Intelligent, circular, and modular temporary architecture transforms from a stand-in to a proactive force for change [23]. According to Martinez and Nguyen [15], the future will be constructed to change rather than to endure. This study provides the framework for that evolution, wherein intelligent, flexible, and lightweight structures provide answers for a world that cannot afford to engage in the same mistakes twice.

1) Critical opinions: Building the unfinished toward a practical future for temporary architecture. Architecture in the twenty-first century is about readiness as much as permanence. This study reinterprets temporary structures as responsive infrastructures indicated for acceleration, sustainability, and socioecological significance rather than using them as stand-ins [5].

2) Urban intelligence as temporality: Function becomes strategy.
Module temporality is redefined as a paradigm shift by the consistent 35% carbon reduction (ANOVA $F=12.7$, $p<0.001$). Eco-modular construction represents architecture of expectancy—a self-cited reimagining of impermanence as strategic foresight—when implemented as responsive 'urban operating systems' for emergencies [15].

3) Ecomodularity: A significant factor.
Modularity has great power. However, when AI and bio-based components are added, it becomes a compound system that can maximize resources, reduce construction time by 40%, and, in the suitable-case scenario, achieve 100% reuse [24]. According to Patel and Kumar [14], these are embodied algorithms rather than merely buildings. Understanding that eco-modularity is a new architectural syntax rather than a component of circular urbanism [25].

4) Adaptive space: From shelter to censorious. The Dubai Pavilion's AI-powered energy logic and the Mobile Marquee's versatility demonstrate how static shelter gives way to living systems—thinking, sensing, and reacting structures. This is not merely spatial design; it is spatial computing [11].

5) Observation: The distinctions between environment, structure, and user [3].

6) Developing emotionally sustainable designs: The beauty of transient structures lies in their temporality—the moment becomes a memory. Examples of how modularity, which is temporary, often encourages aesthetic innovation include cultural icons such as the Serpentine Pavilion [5].
Recognizing that ephemeral does not imply forgettable, something that physically vanishes may endure culturally.

7) Scale as a political instrument: Evidence-based urban policy. The inclusion of temporary ecomodular systems in policy toolkits is strongly supported by the quantitative evidence from this study, which demonstrates 50% energy savings, 75% average reuse, and 35% fewer emissions. These frameworks can bridge the gap between emergency and equality in post-conflict areas, refugee camps, and cities at risk from climate change.

8) Observation: Sustainability is not scalable in the absence of metrics-driven governance [5].

9) Synthesis: The operational temporality framework with three pillars. This study indicates three guiding principles for short-term, future-oriented design:

10) Modularity: for flexibility and sprawl. The preservation of ecological integrity depends on circularity.

11) Maximizing reactivity through the use of intelligence. They establish a new design philosophy known as "operative temporality," which combines accountability, meaning, and acceleration.

12) Final thought: In an era where timelines are collapsing, architecture must be clever by design, circular by ethics, and modular by requirement.

13) Applied case analysis: Expo Dubai's Pavilion of the Future: A setting where temporality and permanence meet. If architecture were to transform the future, it would be similar to this pavilion—ephemeral in form, intelligent in operation, and modular in structure.

Overview of the context

Located in the heart of Expo 2020 Dubai, the Pavilion of the Future was designed to be more than just a structure; it was to be an interactive forecast and a location that would simulate the future urban ecology. It served as a vital experiment for sustainable architecture and drew over 2 million visitors during its brief but impactful existence [11].

Structural logic and modular design.
Composite panels and prefabricated steel built up the pavilion's extremely modular framework, which could be swiftly put up and taken apart at a later time. The form was designed to be a dynamic system that could change size in response to material availability, location constraints, and programmatic requirements [14]. Figure 5 indicates the concept of a temporary concept.

Energy efficiency and artificial intelligence

The AI-powered environmental system in this pavilion was distinctive since it used sensors and algorithms to:

These integrations produced 50% energy savings over passive systems through occupancy-based lighting modifications, HVAC and airflow optimization, real-time energy load prediction, and on-site monitoring [19].

The building was aware that it was using energy.

Circularity and material reuse: Following the tragedy, 85% of the structure's materials were disassembled and used in neighboring municipal and educational buildings. Components were developed with demountable connections and QR tags for traceability to push the boundaries of circular building intelligence. The pavilion was used as an experience of memory-containing materials that could narrate their transformations. Figure 6 shows the intelligence sequence life cycle suggestion for temporary constructions.

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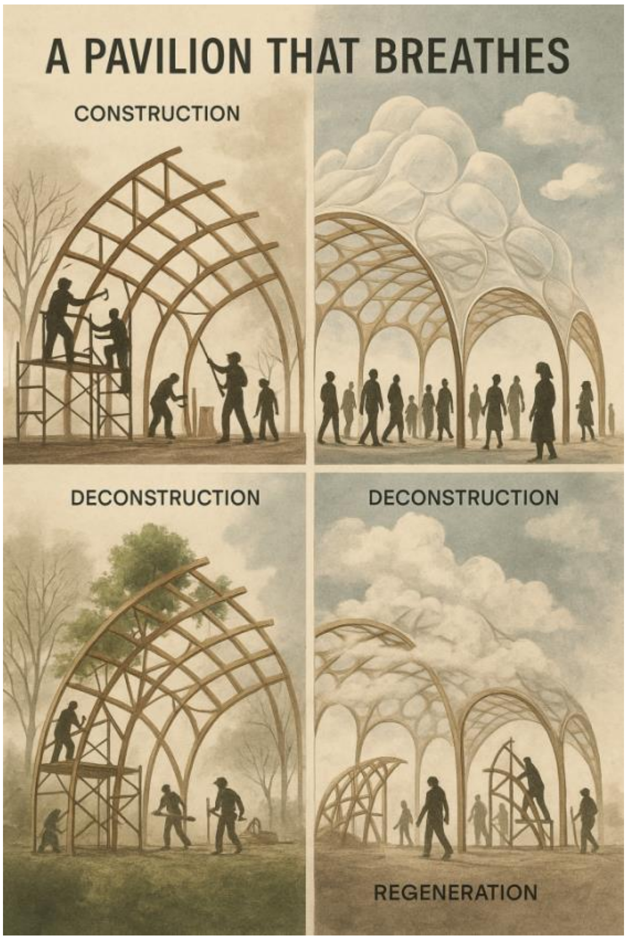

Figure 5. Four stages of architecture, nature, and humanity are combined in this poetic collage: creation, activity, demolition, and regeneration.

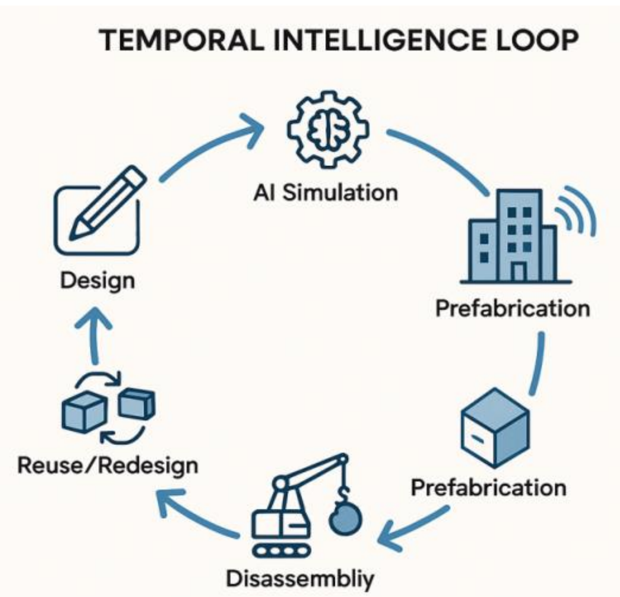

Figure 6. The temporal intelligence loop infographic is a straightforward, circular image that depicts a six-phase architectural life cycle that blends artificial intelligence and sustainability.

The aesthetic of culture and space: The visual style of the structure was abstracted into modern form using parametric techniques, drawing inspiration from desert geometry and arabesque patterning. It created a dialogue between tradition and futurism through immersive zones that each represented a global concern (food, energy, water, and climate). Figure 7 shows the dimensions and objectives of this practical section. The design showed the future and urged people to go through it. Table 4 concludes the main dimensions that should be focused on for successful temporary constructions in the future.

The table emphasizes key performance impacts: 50% energy savings with AI, 40% acceleration of modular construction, 85% material reuse, integration of culture in design, and real-time smart spatial responsiveness.

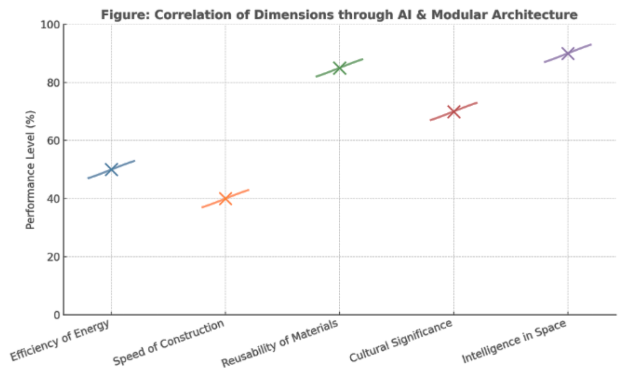

Figure 7. The graphic shows five key performance areas in bright curved lines and colored dots, symbolizing how AI-powered modular architecture changes efficiency. Energy efficiency saw 50% less usage through optimizing algorithms, whereas modular prefabrication enabled a construction process that was 40% faster. Reusability reached 85%, a testament to high sustainability. Cultural relevance is manifested in a blend of current and local values and active spatial intelligence at a high response level, deciding adaptive environments. Together, the image conveys a data-driven, dynamic architectural change.

Table 4. Reflection through analysis.

Dimensions	Impact/Performance
Efficiency of energy	50% decrease through AI optimization.
Speed of construction	Because of modular prefabrication, it is approximately 40% faster.
Reusability of materials	After the show, 85% of the components were reused.
Cultural significance	Combined futuristic expression with regional identity.
Intelligence in space	Data-driven environmental response in real time.

Design perspectives and future applications

- **Replicability:** The system is a modular kit of pieces that may be scaled and adapted for usage in refugee shelters, mobile clinics, and educational pavilions.
- **Technology as fabric:** AI is no longer merely a tool; it is now a material layer of architecture.
- **Temporality as a design approach:** The study demonstrates how ephemeral constructions can impart crucial knowledge regarding efficiency, sustainability, and long-term flexibility.

Finally, rather than being only a temporary building, the Pavilion of the Future is a temporal prototype of permanence. The contrast between "ephemeral" and "enduring" is broken down by showing that the transitory can be remarkably ingenious, beautiful, and practical. It does this by redefining what it means to build for the future—in the future.

Insight results:

Four significant additions to the discipline are made by this study

1. **Conceptual innovation:** By presenting the theoretical framework of "operative temporality," it reinterprets ephemeral design as a durable architectural and urban approach.
2. **Methodological depth:** By combining quantitative performance data (ANOVA, regression) with qualitative theme coding, it connects metrics with meaning.
3. **Consideration of case variation on a global scale:** Analysis and comparison in the document are done with the help of ten case studies from different regions with various climates and weather patterns.
4. **Relevant disciplines beyond architecture:** These areas include urban design, environmental governance, and response to urgent humanitarian needs where sustainability and temporality are interdependent.

Rethinking temporality as strategy: Moving from structures to systems.

CONCLUSION

This study set out to question a basic assumption: Is temporary architecture more than just a band-aid solution? Eco-modularly planned temporary architecture is sustainable and systemically transformational, according to the conclusion made with conviction and clarity from a comprehensive mixed-methods examination that includes statistical validation, case study analysis, and expert insights. The evidence is compelling. Eco-modular constructions resulted in a 35% reduction of carbon emissions, with 50% energy savings due to intelligent system incorporation and a material reuse of 80% to 100%. These constructions reduce the duration of the building process by 30 to 50%. This vision, which goes beyond environmental achievements, is a new dawn for architecture where appearance, use, and presence are in harmony. This study unambiguously demonstrates that ecomodular temporary architecture may meet 21st-century demands for adaptability, sustainability, rapidity, and cultural significance. By combining bio-based materials, modular logic, and smart technology, temporary design becomes an agent of resilience rather than retreat. It is now required to develop transitory architecture as the norm rather than the exception. Future attempts should focus on implementing circular design guidelines. Extending modular AI-powered systems for post-crisis deployment, developing regenerative and biodegradable materials, and incorporating aesthetic discourse and community involvement. This is no longer an intellectual matter but a planetary requirement. Although the empirical findings are very appealing in the given contexts, their generalization needs due consideration of regional climate-related, governmental, and socioeconomic factors in wider applications. What if cities are built to respond instead of to survive? This study shows how temporary structures that are thoughtfully and morally created can have a lasting impact. They're no longer relegated to the background as a piece of the larger machine and now expand outwards towards centrality. When we redefine the impermanent, we begin to construct a resilient and vivaciously cyclical world.

Recommendations

Creating the next urban transition: From data to initiative.

Building on the empirical and conceptual findings of this study, the following recommendations are made to guide future research, design innovation, policy formation, and practical implementation in the field of sustainable temporary architecture:

1) **Establish guidelines for circular architecture:** Disassembly design principles and mandatory material reuse levels should be included in official building regulations for temporary constructions. Cities could adopt urban circularity charters, which are based on the Icehotel and Expo 2020 models, to standardize sustainability parameters in short-term solutions.

Action plan: Incorporate circular economy-related KPIs into the architectural permitting processes.

2) **Utilize modular structures with intelligent technologies:** Architects and engineers must use AI-driven design platforms and IoT-enabled environmental feedback systems to enhance real-time energy optimization, as the Pavilion of the Future illustrates. These technologies should be made available in low-resource locations through open-source endeavors.

Action point: Develop modular toolkits with embedded sensors and AI logic for scale deployment.

3) Invest in bio-based and regenerative materials: Research and development on carbon-negative, self-healing, and biodegradable materials must be funded by governments and academic institutions. Particularly in climate-vulnerable areas, this can increase access to sustainable building solutions, improve circularity, and reduce costs [26].
Action point: Establish cross-sector material innovation laboratories in partnership with green tech firms and academic institutions.

4) Rethink temporariness in urban policy frameworks: In particular, for public space activation, disaster recovery, and refugee resettlement, urban planning agencies should reclassify transitory constructions as strategic infrastructure assets instead of temporary placeholders.
Action point: Include short-term eco-modular systems in national infrastructure resilience strategies.

5) Prioritize design justice and cultural adaptability: In addition to functionality and efficiency, design must reflect local culture, user dignity, and participatory participation. Pop-up green parks and the Serpentine Pavilion are two instances of community-informed modular design that should be replicated and expanded.
Action point: Establish community-involved design guidelines for temporary public architecture.

6) Promote global information sharing:

An open-access digital platform should be established to share metrics, design templates, post-occupancy evaluations, and best practices from temporary eco-modular projects that have been successful all over the world.
Action point: Create a worldwide "Temporary Architecture Observatory" to collect and disseminate scalable case studies.

7) Encourage certification and multidisciplinary training: Specialized instruction in modular design, sustainable materials, circular techniques, and digital design tools ought to be provided by architecture schools and continuing education courses.
Action point: Develop training and certification programs in eco-modular temporary architecture focused on curricula that have already been approved.

8) Engage with probabilistic multi-criteria decision-making tools: To address trade-offs that exist beyond traditional single-metric LCA, engage with probabilistic multi-criteria decision-making frameworks such as the use of fuzzy AHP and Bayesian networks to quantify MCDM for specific eco-modular Contribution of the study: As a result, the current study offers a "primacy empirical contribution" inasmuch as the research uses ten international cases with a "qualitative/quantitative synthesis" in providing a "validated comparative evaluation" with respect to performance indicators and advancing a "triadic framework" or "modularity-circularity-intelligence.

DECLARATIONS

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Declaration of ethics

The study did not involve living human subjects, including vulnerable groups. The subjects of the expert interviews participated with full, informed consent, volunteered to take part, and were assured confidentiality. The low-risk research parameters set by [Amran University] and relevant international standards were adhered to in terms of ethical compliance.

Data availability statement

The results of this study are supported by coded qualitative replies, case study profiles, and quantitative performance indicators, all of which are available upon reasonable academic request. I didn't use any proprietary, confidential, or ethically restricted datasets.

Declaration of generative AI and AI-assisted technologies in the writing process:

Authors of this manuscript utilized the AI tool, ChatGPT, to rephrase a few sentences in the document to improve the clarity and readability of the manuscript. Thereafter, the authors thoroughly analyzed, edited, and polished all the outputs for precision, consistency, and adherence to the goals of the research. Authors declare that they fully assume responsibility for the integrity, originality, and final content of the publication.

Conflict of interest

The author has stated no financial, professional, or personal conflicts that could have influenced the study's integrity or findings.

REFERENCES

[1] Iyer-Raniga U (2019). Using the ReSOLVE framework for circularity in emerging markets. IOP Conf Ser Earth Environ Sci., 294(1):012019. doi: https://doi.org/10.1088/1755-1315/294/1/012019

[2] Brown LG. (2024). From temporary to transformative: How ephemeral structures are shaping global sustainability. Sustain Archit. 12(1):1-18. doi: https://doi.org/10.3390/su12010001

[3] Loonen RCGM. (2024). Climate-adaptive building shells: Responsive façade systems. Renew Archit Rep., 6(1):22-39. doi: https://doi.org/10.1016/j.renarc.2024.01.003

[4] Johnson A, Lee M. (2024). Circular economy in temporary architecture: Redefining sustainability through reuse. J Clean Urban Syst., 16(2):58-74. doi: https://doi.org/10.1016/j.jclepro.2024.141232

[5] Garcia L, Brown R. (2023). Temporary architecture as a tool for community engagement and cultural expression. Urban Futures Rev. 9(3):77-95. doi: https://doi.org/10.1080/14767414.2023.2187645

[6] Thompson R, White L. (2020). Temporality and permanence in architectural theory. Archit Theory Rev.;25(3):301-318. doi: https://doi.org/10.1080/13264826.2020.1854321

[7] Alsharif A. (2019). Prefabrication and sustainability: Rethinking temporary architecture. J Sustain Des.;34(2):121-135. doi: https://doi.org/10.1016/j.jsu.2019.03.002

[8] Lee AJ, Kim DY. (2023). Advancements in modular construction: Enhancing efficiency and sustainability in temporary buildings. J Sustain Archit., 14(4):142-160. doi: https://doi.org/10.1080/2093761X.2023.2189764

[9] Kim S, Park H. (2024). Innovative materials in temporary architecture: Biodegradable composites and smart polymers. Adv Mater Des.;29(1):33-49. doi: https://doi.org/10.1002/adma.202470012

[10] Lee A, Johnson M. (2024). Design justice in temporary urban interventions. J Urban Des.;29(2):145-162. doi: https://doi.org/10.1080/13574809.2024.2314567

[11] Carter J, Smith J. (2023). Smart and temporary: The role of technology in revolutionizing ephemeral architecture. Digital Cities J.;11(4):211-230. doi: https://doi.org/10.1016/j.dict.2023.06.003

[12] Brown, LG, & Green T. (2023). Beyond metrics: A qualitative exploration of aesthetics and creative expression in temporary architecture. Journal of Temporary and Ephemeral Architecture, 8(2), 45–62.

[13] Haakonsen SM, Tomczak A, Izumi B, Luczkowski M. (2024). Automation of circular design: A timber building case study. J Archit Urban., 48(2):95-110. doi: https://doi.org/10.3846/jau.2024.21234

[14] Patel K, Kumar S. (2024). Temporary architecture at world expos: Lessons in modularity and circularity. Int J Sustain Dev., 18(1):101-123. doi: https://doi.org/10.1504/IJSD.2024.138721

[15] Martinez E, Nguyen T. (2024). Temporary buildings as catalysts for sustainable energy solutions. Renew Archit Rev., 10(2):88-107. doi: https://doi.org/10.1016/j.renarc.2024.02.004

[16] Reisach D, Schütz S, Willman J, Schneider S. (2024). Digital fabrication for circular timber construction: A case study. J Circ Econ., 1(2):1-14. doi: https://doi.org/10.55845/VWGD7873

[17] van der Schoor T. (2025). Circular economy in modular construction: An Australian case study. J Build Eng., 103:112182. doi: https://doi.org/10.1016/j.jobe.2025.112182

[18] Zhengyao L, Tsavdaridis KD, Katenbayeva A. (2024). Reusable timber modular buildings: Connection design for circularity. J Build Eng., 98(2):110245. doi: https://doi.org/10.1016/j.jobe.2024.110245

[19] Tzortzis AM, Kormpakis G, Pelekis S, Michalitsi-Psarrou A, Karakolis E, Ntanos C, Askounis D. (2025). AI4EF: Artificial Intelligence for Energy Efficiency in the building sector. SoftwareX. 30:102172.

[20] Barreca F, Arcuri N, Cardinali GD, Di Fazio S, Rollo A, Tirella V. (2022). A highly sustainable timber-cork modular system for lightweight temporary housing. Civ Eng J., 8(Q1):1-15. doi: https://doi.org/10.28991/CEJ-2022-08-01-01

[21] Minunno R, O'Grady T, Morrison GM, Gruner RL. (2020). Exploring environmental benefits of reuse and recycling: A modular building case study. J Clean Prod., 247:119131. doi: https://doi.org/10.1016/j.jclepro.2019.119131

[22] Hamida MB, Jylha T, Remoy H, Gruis V. Circular building adaptability and its determinants: A literature review. (2022). Int J Build Pathol Adapt., 41(6):47-69. doi: https://doi.org/10.1108/IJBPA-11-2021-0150

[23] Sigurd Naess-Schmidt H, Haahr JH, Hvid N, Nejland TL. (2022). Housing market analysis and circular renovation. Eur Environ Agency. https://www.eea.europa.eu/publications/circular-renovation

[24] Vahdatikhaki F, Salimzadeh N, Hammad A. (2024). Generative design for energy-efficient offices using parametric louvres. J Daylighting. 11(1):45-60. doi: https://doi.org/10.15627/jd.2024.4

[25] Genkin M, McArthur JJ. (2022). B-SMART: A reference architecture for artificially intelligent autonomic smart buildings. Engineering Applications of Artificial Intelligence, 121:106063.

[26] Palumbo J. (2021). Tecla House: 3D-printed circular housing prototype. CNN. https://edition.cnn.com/style/article/tecla-3d-printed-house/index.html