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Foreword

La universidad jesuita como testimonio de esperanza

Vivimos la prevalencia de ciertas hegemonías globales con enormes repercusiones locales que lastiman y hieren la dignidad de las personas y la propia naturaleza de la humanidad. El capitalismo salvaje, el antropoceno, los neofacismos y neocolonialismos, las violencias, el patriarcado. ¿Qué papel juegan las universidades en un mundo cada vez más hostil para el pensamiento crítico y la creación de conocimiento para resolver los graves problemas de la humanidad?

Para las universidades jesuitas como la Universidad Iberoamericana Torreón, *la primera asignatura de la universidad es la realidad*. La universidad jesuita es contextual, nos debemos a nuestro entorno. La realidad que nos circunda se convierte en horizonte epistemológico en el que disciplinas y profesiones buscarán comprender la complejidad de la realidad para intervenir en ella y afectarla positivamente en una agenda en la que prevalezca la esperanza de un mundo más justo y fraterno.

El Papa Francisco, el primer Papa jesuita de la historia publicó en su encíclica *Laudato Si* la hipótesis de que la crisis ambiental del mundo era al mismo tiempo una crisis social. Animó a recuperar la defensa de los bienes naturales y articuló en torno a la categoría “cuidado de la casa común” un conjunto de activismos, investigaciones, incidencias y proyectos que avanzaron en distintos ejes de acción como la sustentabilidad, el decrecimiento, la economía social y solidaria, el comercio justo, entre otras muchas epistemologías para atajar los efectos del cambio climático, los proyectos extractivos y extractivistas y la desinformación negacionista en torno al antropoceno.

Por ello, la Ibero Torreón está convencida que hay que responder a este contexto con tres estrategias universitarias: a) la universidad como ágora pública; b) la universidad como ejemplo de sustentabilidad; c) la universidad como proveedora de sentido esperanzador.

En medio de las violencias que vemos en el mundo y en nuestro país, la mejor respuesta universitaria es el sostenimiento de la cultura del diálogo, el encuentro de lo diverso y heterogéneo, la construcción de acuerdos entre intereses contrapuestos. Nuestra universidad se ha convertido en ágora pública para que en su campus diferentes actores gubernamentales, empresariales, sociales y eclesiales digan su palabra, desarrollen eventos y agendas y propongan soluciones a las principales problemáticas de nuestro tiempo.

Nuestra universidad, la Ibero Torreón, es la tercera universidad privada más sustentable de México al cierre del año 2025, según el ranking mundial de campus sustentables Green Metrics. Con ello, nuestra casa de estudios quiere ser la primera en avanzar en nuestros aportes de sustentabilidad y dotaciones de bienes ecológicos y ambientales a nuestra región, como el ser el segundo pulmón verde de la ciudad y generar energía limpia. Lo que queremos que suceda afuera, primero lo hacemos con nuestra casa.

La universidad jesuita no se erigió sólo para entregar títulos universitarios sino para formar hombres y mujeres capaces para los demás. Nuestra apuesta es formar mejores personas para que esos sujetos competentes, conscientes, compasivos y comprometidos incidan positivamente en la realidad para transformarla dignamente.

Así entonces nuestro proyecto educativo busca ser un proyecto esperanzador en tiempos de desesperanza y alentar con educación situada la compresión de los problemas para erigir las mejores propuestas de solución.

Por ello celebramos que nuestra universidad haya sido sede de un gran evento internacional en el que la reflexión/acción estuvo en torno a la vivienda sustentable, la energía cero, la revolución tecnológica entorno a la vivienda, las condiciones de un hábitat digno y replicable sobre todo para los sectores más vulnerables de la población.

Deseamos que los horizontes epistemológicos de este foro internacional impacten en el cambio de vivienda que necesitamos sobre todo en contextos de extremos climáticos. Refrendamos nuestro compromiso para que Ibero Torreón siga sosteniendo una presencia esperanzadora donde más se necesita.

“La Verdad Nos Hará Libres”

Mtro. Juan Luis Hernández Avendaño
Rector
Universidad Iberoamericana Torreón

Prologue

At a historic moment defined by climate urgency, accelerated urbanization, and the need to fundamentally rethink our development models, housing emerges as one of the most strategic arenas for sustainable transformation. This publication brings together valuable contributions from researchers across the globe who, from diverse disciplines and contexts, reflect on a shared challenge: the design and implementation of customized zero-energy mass housing.

This compilation not only documents technical and methodological advances but also reveals a conceptual evolution: the transition from standardized housing models toward solutions that integrate energy efficiency, cultural identity, social adaptability, and environmental responsibility. Housing is no longer understood as a repetitive product, but as an intelligent system—one that is responsive to its environment and capable of addressing the specific needs of its inhabitants without compromising the planet's ecological balance.

The papers gathered here engage in dialogue through perspectives that encompass technological innovation, urban planning, environmental engineering, circular economy, and architectural design. Together, they offer a comprehensive vision of what it means to conceive serial housing that not only reduces its energy impact but aspires to eliminate it—without sacrificing spatial quality, economic feasibility, or social relevance.

In this context, customization no longer stands in opposition to mass production; rather, it becomes its natural evolution through digital tools, advanced industrialized processes, and new knowledge management models. Zero energy, in turn, moves beyond a utopian aspiration to become an achievable horizon through the integration of passive design, renewable energy, and efficient construction systems.

From the Universidad Iberoamericana Torreón, we celebrate the creation of this space for academic convergence that fosters critical thinking, international collaboration, and the pursuit of concrete solutions to global housing challenges. We trust that the ideas presented here will not only enrich academic discourse, but also inspire public policy, industrial strategies, and architectural proposals aimed at a more just and sustainable future.

We also extend our sincere appreciation to Dr. Masa Noguchi, whose intellectual leadership has been instrumental in the development of the ZEMCH (Zero Energy Mass Custom Home) concept. His vision has played a decisive role in shaping a global agenda that connects technological innovation with social and environmental responsibility in housing, inspiring researchers, institutions, and professionals to rethink traditional paradigms of residential production.

May this book serve not only as a testament to current knowledge, but also as a starting point for new research, alliances, and transformative action.

Sincerely,

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CHAPTER 1

SUSTAINABLE ARCHITECTURE AND URBAN DESIGN

INTEGRATING URBAN AGRICULTURE INTO RESIDENTIAL FABRICS: DENSITY-BASED POTENTIAL IN AL AIN, UAE

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ABSTRACT

Urban agriculture is gaining prominence to strengthen food security, environmental sustainability, and urban resilience, particularly in rapidly developing regions. This study investigates the potential for integrating urban agriculture into residential neighborhoods in Al Ain City, located in the hot-arid climate of the United Arab Emirates. The research aims to assess how urban form and residential density influence the feasibility of incorporating productive green infrastructure. A spatial analysis was employed to examine neighborhood typologies across low-, medium-, and high-density zones, using parameters such as building footprints, open space availability, and proximity to community facilities. Findings indicate that low- and medium-density areas provide more favorable conditions for decentralized urban agriculture, including backyard gardens, rooftop systems, and communal green plots. High-density zones pose spatial challenges but offer opportunities for vertical and rooftop farming with appropriate support. The study identifies suitable zones for pilot implementation and proposes a scalable framework tailored to different urban densities. By aligning urban agriculture strategies with neighborhood characteristics, the research contributes to localized food system development and sustainable land use planning in the UAE. The results support broader national goals of enhancing urban livability, adaptive urban design, and long-term food resilience.

Keywords: Urban Agriculture; Residential Neighborhood Density, Spatial Analysis, Sustainable Urban Design, Food Resilience

1. Introduction

The global rise of urbanization and climate pressures is prompting cities to reassess how land is used and how food is sourced. Urban agriculture (UA)—the practice of cultivating, processing, and distributing food in or around urban areas—presents a promising solution to food security and sustainability challenges. In rapidly urbanizing regions, UA offers decentralized food production, reduces food miles, and enhances access to fresh produce (Ghimire, 2024). It also fosters community resilience by engaging local populations in food production and strengthening social networks (Khan et al., 2024). Furthermore, UA contributes to addressing nutritional needs, mitigating urban poverty, and supporting environmental initiatives such as urban greening, waste recycling, and climate adaptation (Marzban et al., 2024).

Urban–agro greening has evolved from Howard's Garden City concept (Howard, 1902), through mid-20th century ecological planning (McHarg, 1969), to contemporary agro-urbanism integrating food systems into city morphology (Viljoen & Bohn, 2014). Despite this trajectory, gaps remain in addressing arid-climate contexts where land, water, and socio-cultural factors complicate adoption. Urban agriculture in arid climates faces recurring challenges including land-use conflicts (Opitz et al., 2016), water scarcity and resource efficiency concerns (FAO, 2019), and socio-cultural barriers to wider adoption (Sanye-Mengual et al., 2018). While such studies highlight the promise of UA in desert cities, questions of scalability and spatial integration—particularly in relation to residential density and neighborhood form—remain unresolved. In the Gulf context, recent studies have shown that household-based UA persists largely informally, shaped by cultural preferences and limited policy support; such practices, while fragmented, highlight both barriers to formal adoption and opportunities for integration within residential fabrics (Alfzari et al., 2023; ; Alhaddad & Ahmed, 2024).

In response to such challenges, the United Arab Emirates (UAE) launched its National Food Security Strategy 2051, aiming to transform the country into a global leader in food security through innovation, boosting local food production, and reducing dependency on imports (National Food Security Strategy 2051, 2025). Nevertheless, the country's hot and dry weather conditions continue to present significant barriers to sustainable agriculture, food security, and resource efficiency (Ammar et al., 2024). In this context, cities like Al Ain—characterized by hot-arid conditions and diverse residential typologies—offer valuable opportunities for UA to enhance local food production, improve water efficiency, and support climate resilience. UA can also serve as a catalyst for transforming urban public spaces into multifunctional green infrastructure that promotes social cohesion, ecological health, and adaptive urban environments (Ghahremani et al., 2024). However, the effective integration of UA into existing urban fabric requires localized, context-sensitive planning that accounts for density patterns, neighborhood types, and spatial constraints.

Integrating agriculture within UAE context's residential fabric is particularly urgent given the country's reliance on imported food (≈90%), rising urban heat island effects, and local aspirations for cultural revival of oasis traditions (Alawadi, 2017). Unlike temperate global cases, Al-Ain combines extreme aridity with low-density sprawl, making agro-integration both unique and challenging. Given Al Ain's urban form and climatic context, potential UA strategies include rooftop gardens, vertical farming, hydroponic systems, aquaponics, green facades, container farming, as well as private and community gardens—each adapted to specific urban densities and available space (Despommier, 2010; Orsini et al., 2013). High-density neighborhoods may benefit from rooftop and vertical systems, whereas low-density and peri-urban zones are more suitable for shared community gardens, agroforestry, or integrated land-based farming.

Despite the UAE's national ambitions, urban planning frameworks at the local level have not yet fully incorporated UA as a priority. To facilitate UA adoption, urban strategies must explore new zoning incentives, integrate UA into green infrastructure plans, and make use of underutilized urban spaces such as private gardens, semi-private rooftops, and public vacant plots. Existing studies reveal that even in the absence of formal frameworks, informal and household-based UA practices are already emerging in Emirati neighborhoods, especially in villa-dominated areas where space availability and cultural preferences support such practices (Alfzari et al., 2023; Alhaddad & Ahmed, 2024).

This study therefore asks: How can agro-urban strategies be adapted to Al-Ain's residential density patterns to identify suitable pathways for integrating urban agriculture into the existing urban fabric? This study builds on these insights and assesses the spatial readiness of residential zones in Al Ain, UAE, for the integration of urban agriculture. It analyzes neighborhood typologies based on density to evaluate their suitability for various UA practices, aiming to inform planning frameworks that better align UA strategies with urban morphology

2. Methodology

This study adopts a spatial typology-based analysis to assess the potential for integrating urban agriculture (UA) across various residential densities in Al Ain, United Arab Emirates. The approach builds on existing methods used in evaluating urban morphology and green infrastructure integration in arid regions (Alhaddad & Ahmed, 2024; Säumel et al., 2019), focusing specifically on the spatial conditions that enable or constrain productive green uses within the built environment. Spatial data were obtained from multiple sources, including Google Earth satellite imagery, official land-use maps provided by Al Ain Municipality and the Department of Municipalities and Transport (DMT), and statistical datasets from the Statistics Centre – Abu Dhabi (SCAD). These sources were cross-referenced to establish a consistent classification of residential neighborhoods by density, enabling a comparative analysis of urban form.

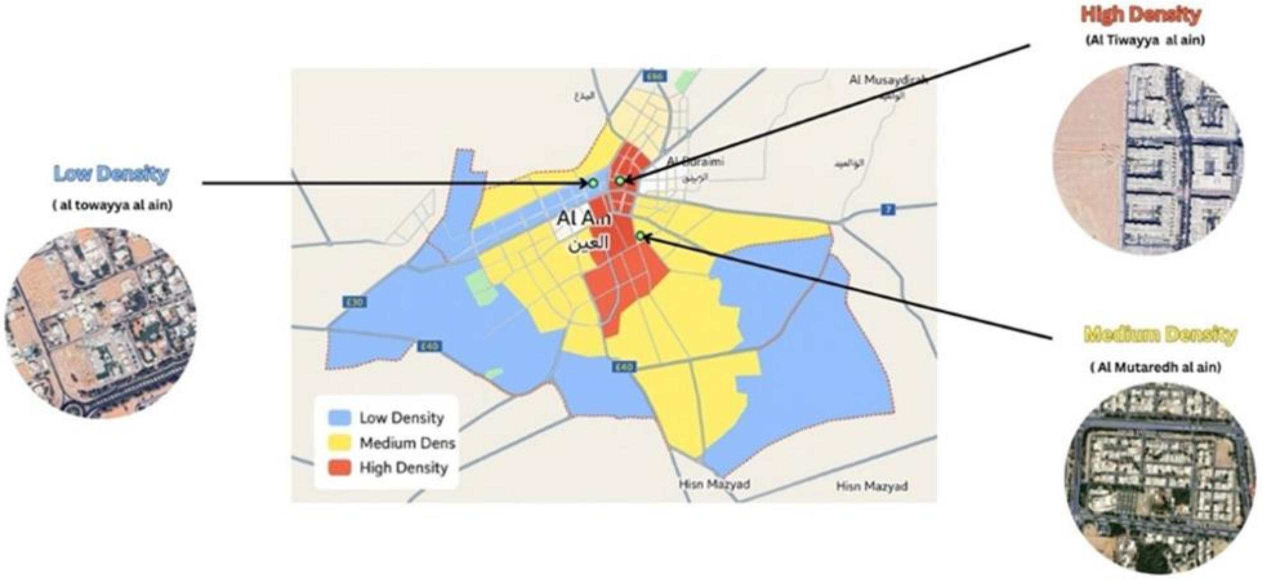
In addition, a case study approach was applied to Al-Ain using satellite-based spatial analysis. The assessment considered land-use maps, building footprints, and climatic data from UAE MOCCAE, with spatial measures such as green cover percentage, floor area ratio (FAR), and solar exposure derived through GIS layers.

Figure 1 illustrates the spatial distribution of low-, medium-, and high-density neighborhoods in Al Ain, derived from the integration of satellite imagery and municipal land-use zoning. This mapping supports the density-based segmentation and informs subsequent suitability assessments for urban agriculture integration.

Neighborhoods were categorized into low-, medium-, and high-density zones based on a combination of indicators such as building footprint coverage, average plot size, and the ratio of green to built-up space. For each category, a representative area was selected: Al Towayya and Zakher for low-density, Al Mutaredh and Al Jimi for medium-density, and the vicinity of Al Ain Mall and Hazza Bin Zayed Stadium for high-density. This typological distinction aligns with conventional urban density definitions and is supported by similar frameworks in previous urban sustainability research (Li & Carter, 2025).

Within each typology, specific spatial parameters were analyzed to determine UA suitability: the proportion of planted versus unplanted land within residential plots, the availability of rooftops and courtyards, and proximity to public or semi-public open spaces. These metrics were used to evaluate the potential for deploying different UA methods, including backyard gardens, rooftop hydroponic systems, vertical farming on facades, and community plots. This analysis offers a spatially grounded understanding of where and how UA can be integrated, while adapting density-responsive approaches to the hot-arid context of Al-Ain, echoing methods used in density-responsive green infrastructure studies. By framing the investigation around density and land use, the study proposes a context-sensitive framework that aligns UA strategies with urban morphology. This approach supports municipal-scale planning that enhances food security and environmental resilience in desert cities like Al Ain.

Figure 1: Residential Neighborhood Density Classification in Al Ain, UAE.



3. Results and Discussion

The spatial analysis revealed distinct urban agriculture (UA) integration potentials across low-, medium-, and high-density residential typologies in Al Ain (Figure 1).

Low-density areas (e.g., Zakher, Al Towayya) offer the highest suitability for decentralized UA due to expansive plot sizes and significant proportions of plantable and unplanted land (27.23% and 25.44%, respectively; see Table 1). These areas are conducive to backyard farming, greenhouse installations, and aquaponics, supported by ample space and relative privacy. However, adoption may be constrained by aesthetic landscaping preferences and low public awareness, as also reported by Sharjah Sustainable City (2022).

Medium-density zones (e.g., Al Jimi, Al Mutaredh) demonstrate balanced potential, with approximately 20% green or plantable area per parcel. These neighborhoods, comprising townhouses and small apartment blocks, support semi-shared UA models such as rooftop gardens, courtyard hydroponics, and community-managed green spaces. However, implementation hinges on coordinated governance, tenant-landlord agreements, and zoning adaptability—challenges previously identified in regional UA literature (Khan et al., 2018; Alhaddad & Ahmed, 2024).

High-density districts, such as those near Al Ain Mall and Hazza Bin Zayed Stadium, face spatial constraints, with only 12% green planted areas and high land coverage (53% residential). Nonetheless, innovative and technology-driven systems—such as vertical farming, rooftop hydroponics, and smart indoor agriculture—can still be deployed (Gomathy et al., 2024). Controlled Environment Agriculture (CEA) and modular vertical units are particularly relevant here, where land scarcity coincides with high population pressure.

A comparative typology analysis (see Table 1) suggests the need for a density-responsive integration strategy. Low-density areas are suited for private gardens and greywater-fed greenhouses. Medium-density zones can pilot shared rooftop or courtyard systems, while high-density areas demand capital-intensive but scalable innovations like green walls and facade farming. The framework aligns with

Despommier's (2010) proposition for vertical farming as a viable urban solution and resonates with studies highlighting the multifunctional potential of UA in arid cities (Säumel et al., 2019).

Table 1: Summarizes the spatial features and integration potentials by neighborhood density type.

Density Type	**Residential Area Characteristics**	**Green Area/Urban Agriculture Potential**	**Typical Integration Methods**	**Challenges & Opportunities**	**Percentage %**			
					Residential Areas	**Green Planted areas**	**Unplanted areas**	**Plantable areas inside plots**
Low Density	- Large plot villas, detached houses	- Ample private gardens, yards	- Traditional gardens - Rooftop farming - Community gardens	- High potential for private and community farming - Residents prioritize recreational/aesthetic use over food production - Water use can be high, but space allows for experimentation with new methods	29.03%	18.30%	27.23%	25.44%
Medium Density	- Townhouses, small apartment blocks - Mixed-use developments	- Shared green spaces - Courtyards - Small community gardens	- Shared rooftop farms - Vertical gardens on facades - Urban community plots	- Moderate space for agriculture - Requires community coordination - Potential for integrating hydroponics or vertical systems in shared spaces	50%	20%	20%	10%
High Density	- High-rise apartments, dense urban cores	- Limited ground-level green space - Rooftop and vertical surfaces	- Vertical farming - Hydroponics/aeroponics in basements or rooftops - Green walls	- Space constraints require innovative solutions - High potential for advanced tech (vertical farming, hydroponics) - Can contribute to food security and urban cooling	53%	12%	23%	12%

At the same time, the analysis highlights several impediments that condition the feasibility of UA in Al-Ain. Physical constraints include limited available space and the shading effects of adjacent buildings, while functional issues arise from the added demands on irrigation networks, infrastructure, and zoning regulations. Environmental trade-offs must also be acknowledged, since the benefits of improved air quality and cooling may be offset by higher water consumption in a desert city. Framing these challenges within a DPSIR perspective emphasizes how drivers such as food security and cultural revival interact with pressures like land scarcity and climate stress, producing a fragmented urban fabric whose impacts include competition for space and increased resource demand. The necessary responses involve targeted zoning reforms and investment in efficient irrigation technologies to support long-term integration. Vertical farming integrated into multi-story blocks could compensate for poor soil fertility, though structural retrofitting and high energy demand remain barriers (Despommier, 2010; Al-Kodmany, 2018). Comparative evidence from Singapore's agro-terracing model illustrates feasibility in high-density settings (Yuen & Hien, 2005).

In addition to physical space, social acceptance and governance mechanisms emerged as critical enablers of UA. Uptake in low-density zones may depend on shifting resident priorities from aesthetics to productivity. In denser areas, formal policy tools and design regulations are required to institutionalize UA infrastructure within building codes and urban planning frameworks. Cross-sector collaboration—especially between planners, environmental engineers, and housing authorities—is essential for enabling long-term adoption and equitable access to urban food systems.

4. Conclusion

This study assessed the spatial readiness of residential neighborhoods in Al Ain for urban agriculture (UA), demonstrating how residential density patterns shape opportunities and constraints for implementation. Through density-mapping and land-use analysis, the findings highlight that low- and medium-density areas are best suited for decentralized practices such as backyard, rooftop, and community farming, while high-density zones require innovative, technology-driven approaches including vertical and indoor systems. By linking UA typologies directly to density categories and identifying impediments related to spatial limitations, infrastructure pressures, and resource trade-offs, the study provides a density-responsive framework to guide policy and planning. Overall, this contribution offers practical guidance for integrating UA into existing urban fabrics while supporting the UAE's broader goals for food security, adaptive planning, and sustainable development.

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A QUANTITATIVE CHARACTERIZATION OF THE LUMINOUS AND THERMAL ENVIRONMENTS OF FERNAND POUILLON'S ZIBAN HOTEL (BISKRA, SOUTHERN-EAST ALGERIA).

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ABSTRACT

Fernand Pouillon's hotel architecture has often been praised for its formal richness and the quality of spatial atmospheres it creates. However, limited research has focused on the objective assessment of the physical environments it generates. This study quantitatively characterizes and evaluates luminous and thermal comfort in the Ziban Hotel in Biskra, located in a semi-arid region with a hot and dry climate. The methodological process included creating a 3D digital model of the building followed by simulations of its thermal and luminous environments. These simulations, conducted with computer-based tools, focused on indices such as daylight autonomy, natural light distribution, indoor temperature, and the efficiency of passive systems. Among the hotel's spatial sequences, simulations were carried out for those identified by users as the most memorable, based on a prior in-situ qualitative survey. The results highlight Pouillon's sensitivity to climatic constraints in his architectural design and the building's environmental adaptability. At the same time, the quantitative assessment reveals significant variations in thermal and luminous conditions, providing users with specific sensory experiences. These contrasting atmospheres reflect the relationship between interior and exterior environments characteristic of the region and its vernacular architecture.

Keywords: Thermal, luminous, hotel, hot-arid climate, Fernand Pouillon.

1. Introduction

Fernand Pouillon’s architecture in Algeria, particularly in the tourism sector, stands out for its sensitive design approach (Zineddine, 2019). His work combines constructive rationality, site-specific adaptation, and the integration of local resources (Kaihoul & Sriti, 2024). Several studies have highlighted the richness of the architectural vocabulary employed in his hotel projects, as well as the quality of atmospheres generated through specific architectural devices (Zineddine & Belakehal, 2019). Most of these investigations have explored the qualitative dimension of comfort, based on user perceptions gathered through immersive methods such as guided walkthroughs. These methods allowed researchers to identify and interpret the most significant spatial sequences in Pouillon’s hotels (Zineddine et al., 2022).

Building on this previous research, the present study adopts a complementary perspective focused on the quantitative characterization of Pouillon’s hotel interiors. More specifically, it evaluates luminous and thermal environments through numerical simulations applied to the Ziban Hotel, designed by Pouillon in 1969 in Biskra (southeastern Algeria). Within this semi-arid, hot climate, the building offers a relevant case for examining how contemporary architecture can respond to local environmental constraints.

The outcomes of this study contribute to: i) enhancing the understanding of the atmospheres created by Pouillon’s architecture in hot, dry climates; and ii) providing insights into climate-responsive design principles within the framework of contemporary architectural heritage.

2. Methodology and simulation protocol

This research relies on numerical simulations to evaluate the physical environmental characteristics (temperature and luminance) of a memorable spatial sequence inside the Ziban Hotel in Biskra (Figure 1). This sequence was identified through an in-situ user survey, known as the “commented path,” similar to the method previously applied at the El Mountazah Hotel, another hotel designed by Pouillon, but located on the northern-east Algerian coast (Zineddine et al., 2022). Two software programs were used: i) Ecotect 5.5 (2005) for thermal simulations, and ii) Radiance (2.0 Beta) for daylight simulations.

Radiance simulations considered an eye level corresponding to a user standing position (1.70 m) (Mohelníková & Vajkay, 2008, Ward, 1994). The simulation protocol adopted for this sequence's study has been applied for the investigation of a different path in the same hotel including seven other different spatial sequences (Zineddine et al., 2018). In addition, seasonal variations were taken into account and simulations were therefore carried out for the two equinoxes (June 21 and December 21). These correspond to the most contrasting periods of the year, combining climatic points of view and local tourist activity.

2.1 Protocol of simulation

A 3D digital model of the selected sequence was reconstructed in Ecotect 5.5, integrating its morphological features—shape, volume, materials—as well as the type, size, number, and orientation of openings (Figure 2, Table 1). The studied sequence covers an area of 190 m^2 (13 m × 14 m, with a height of 2.60 m). It includes three large glazed bays providing natural light and ventilation. One of the east-facing openings is equipped with manually operated curtains, allowing controlled adjustment of daylight (Table 1). It should be noticed that this space is equipped with air conditioning units, which were not installed when the hotel was put into service, nor provided for in its initial design. Consequently, they were considered switched off in the simulation process during the selected period.

The local meteorological data for Biskra, provided in the Weather Data File (TMY_Biskra-hour.epw), were imported into the software to ensure realistic simulations consistent with the site's hot and dry climate (Meteonorm, 2018). The simulations were carried out under clear-sky conditions, which characterize the local semi-arid climate (www.satel-light.com). In Radiance, this was represented using the Perez clear-sky model (Perez& al 1993), to ensure consistency with climate-based daylighting simulations. No internal gains or artificial lighting were included, and occupancy schedules were omitted since the analysis focused on the 16:00–18:00 time window. Natural ventilation was assumed through the east- and northeast-facing openings. Shading was modeled as static open curtains, without dynamic control.

The reliability of such digital daylight simulations has been attested by previous comparative studies between numerical and physical scale models (Mezerdi & Belakehal, 2017; Berghout et al., 2014; Brembilla et al., 2022; Monteoliva et al., 2021). In the present study, no on-site measurement data were available for calibration; however, the input parameters were based on verified archival and climate data, ensuring coherence with established references. Future work should include short-term in-situ logging of temperature and luminance to validate and refine the simulation results. The simulation scenario was defined in accordance with the in-situ survey, and this specific timeframe was selected to match the observed peak user presence during the last week of May 2018 in Biskra. Additional simulations at seasonal milestones (summer and winter solstices) were also performed to check whether these comfort patterns persist throughout the year. At this time of day, significant variations in temperature and natural light (including both direct sunlight and diffuse daylight) are observed (Zineddine et al., 2018). Focusing on the macro visual field, the luminance simulations examined the visual components perceived by a moving observer within the sequence (Bonham, 2013). This approach allows the assessment of the actual perceived lighting quality of this emblematic architectural component in the simulation.

Figure 1: Ground floor Plan view of the reception hall of the Ziban hotel (memorable sequence 1)

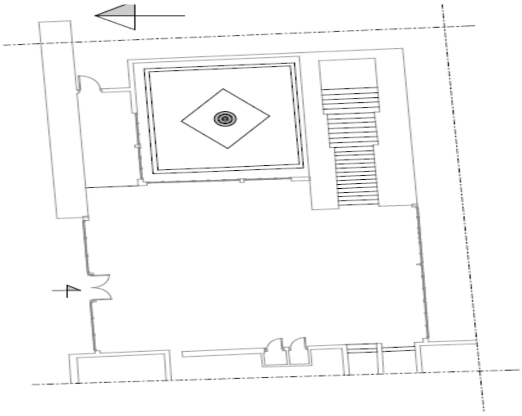
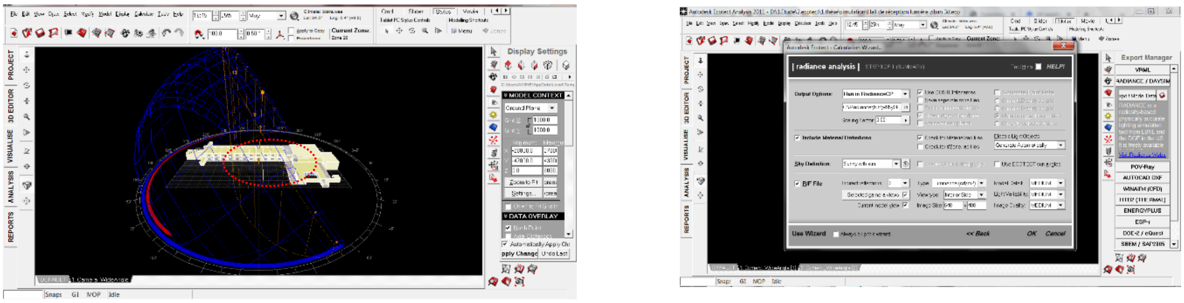


Table 1: Morphological features of the reception hall of the Ziban Hotel

Number of openings / orientation	Typology of openings	Size of openings	Arrangement of openings
01 facing south 02 facing east 03 facing northeast	Rectangular shape (Side daylighting)	1) 10 x2.60 2) 8x 2.60 3)8x2.6	Centrally located in the room's wall

Figure 2: Simulation model of the Ziban Hotel reception hall using Ecotect 5.5



The data related to building materials used in the hotel were extracted from municipal archives (A.E.T.A, 1968). Their optical and thermal properties required for simulations were defined based on extensive literature review (Table 2).

Table 2: Physical characteristics of the building materials used in the Ziban Hotel

Construction Materials	Layer Thickness (m)	Density (kg/m^3)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)
Brick	0.20	650	1000	0.39
Rustic Lime Plaster	0.012	1600	850	0.70
Glass	0.004	2500	1000	1
Common Gypsum Plaster	0.06	1150	1008	0.57
Granite	0.10	2500	1008	3.5
Marble	0.03	2800	800	2.91–3.5
Mortar	0.20	2000	1008	1.3
Solid Slab	0.10	2000	1008	1.8
Wood	0.04	500	1800	0.14
Concrete	0.10	1.8–2.5	900	1.8

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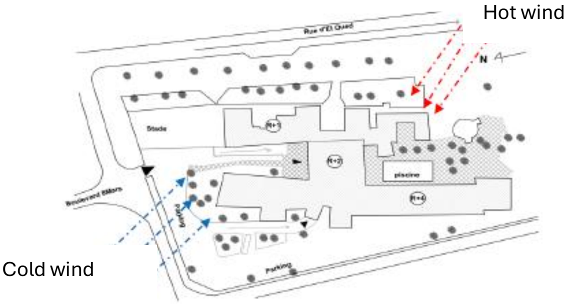
2.2 Case study

Built in 1969, the Ziban Hotel is located near the Sidi Zarzour River, close to the center of Biskra. At the time of its construction, it was surrounded by vacant land, except for a southern palm grove and a football stadium dating from the French colonial period (Figure 3). The site benefits from cool northwesterly winds in winter but is exposed to hot, dusty southeasterly winds during summer (Figure 4).

Figure 3: The Ziban hotel facade giving on the swimming pool.

Figure 4: View of the site plan and prevailing winds of the Ziban



The architectural layout follows an H-shaped plan, oriented along a north–south axis, with an introverted spatial organization. The building has four levels: service areas on the ground floor, the reception on the first floor (accessed by a ramp), and guest rooms on the upper levels. According to surveyed users (Zineddine, 2019), the reception hall represents the most memorable spatial sequence of the hotel.

3. RESULTS AND DISCUSSION

3.1 . Daylight

The daylighting simulations generated a set of false-color and grayscale images using Radiance, illustrating the spatial distribution of luminance values within the macro visual field at eye level (Figure 5).

Figure 5: Example of false-color simulations (1) and grayscale photographs (2) of natural light in the macro visual field – Reception hall of the Ziban Hotel (May 25, 2016)

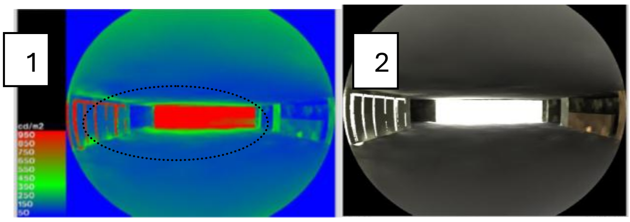
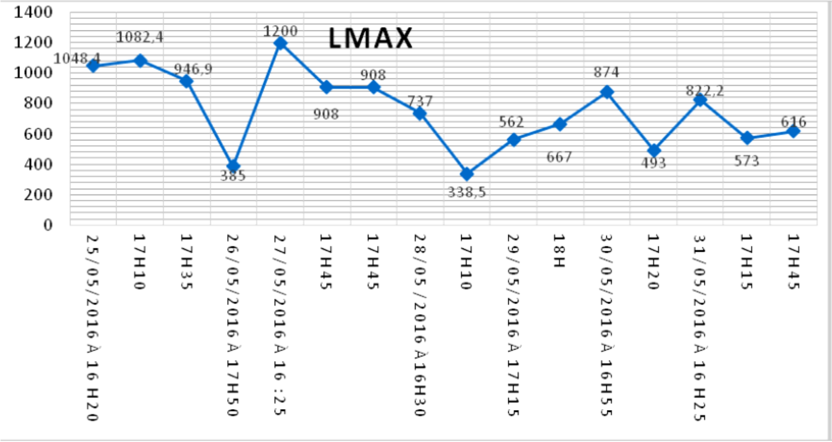


Figure 6 shows that peak luminance values in the reception hall frequently range between 500 to 1,000 cd/m^2. In some cases, values reached up to 1,200 cd/m^2, indicating situations of high luminous contrast and strong light exposure, particularly during late May afternoons. These results confirm the presence of glare, according to established thresholds (Fontoynont, 1999; Berruto, 1996), although the overall lighting distribution remained relatively uniform (Figure 6).

Figure 6: Variation of luminance values [cd/m^2] at different times of day in the reception hall of the Ziban Hotel



Referring to the Daylight Glare Probability (DGP), such luminance levels correspond to values above 0.40, revealing perceptible to disturbing glare conditions (Wienold & Christoffersen, 2006). Despite the generally uniform daylight distribution across the hall, these findings confirm a significant risk of localized glare that occurs at the late-afternoon hours.

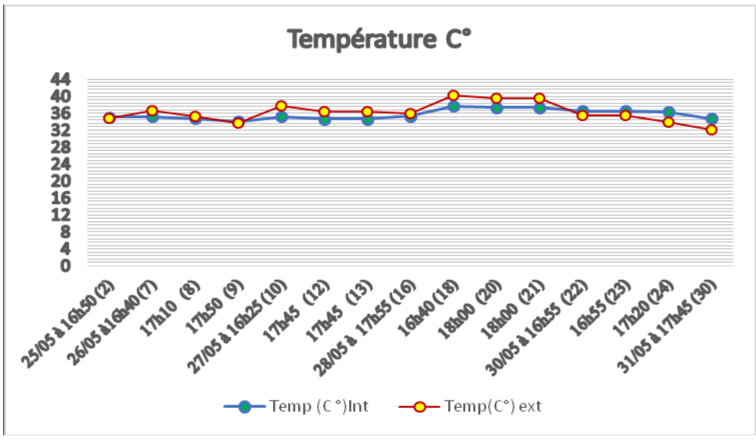
Overall, this luminous spatial configuration—supported by bilateral daylighting, by means of large glazed openings and diffuse reflections from light-colored surfaces, creates a dynamic visual atmosphere. In addition, the view outside, towards the swimming pool, seems to mitigate glare perception while providing a calming focal point and enhancing visual comfort (Figure 7).

Figure 7: View outside from the Reception hall in the Ziban Hotel.

3.2 Temperature

Thermal simulation outcomes indicate that the reception hall is characterized by high indoor temperatures, ranging from 34°C to 38°C (Figure 8). Recorded values fluctuated between 34.1°C (May 26, 5:40 p.m.) and 37.7°C (May 28, 4:40 p.m.). In certain instances, indoor temperatures were up to 2.5°C lower than outdoors, while in others they slightly exceeded outdoor conditions, with differences of –2.7°C (May 30, 4:55 p.m.) to –0.2°C (May 25, 4:50 p.m.).

Figure 8: Ambient temperature [°C] values recorded by users in the memorable sequence (reception hall) of the Ziban hotel



Thermal comfort was evaluated using the adaptive model from ASHRAE Standard 55 (2020) and EN 16798-1. For naturally ventilated spaces in hot semi-arid climates, when the monthly mean outdoor temperature is about 30 °C—as in Biskra during summer—the upper comfort limit is around 32 °C (derived from the adaptive model equations and charts, not a fixed value). In this study, operative temperatures in the reception hall ranged between 34 °C and 38 °C, thus consistently exceeding the adaptive threshold and indicating significant overheating risk. The percentage of hours above the adaptive comfort threshold (32°C) exceeded 70% during simulation days.

These findings show that while architectural features such as favorable orientation, proximity to a palm grove, and the cooling effect of the pool help moderate conditions, they remain insufficient to ensure thermal comfort. The northeast-facing openings promote cross-ventilation, and in winter, the massive walls with rubble infill provide strong thermal inertia. Together, these elements partially improve comfort, yet the hall remains overheated during late spring afternoons when unconditioned.

From a practical perspective, several rehabilitation measures could improve simultaneously both luminous and thermal comfort in hot and semi-arid climates under clear-sky conditions as it was experienced in similar climatic contexts. For instance, the use of low-SHGC glazing has proven particularly effective in the arid context of Jeddah (Saudi Arabia). In fact, the advanced glazing systems reduced peak indoor temperatures by up to 8.3 °C compared to conventional glass (Alwetaishi & al, 2024). In addition, adaptive dynamic façades, including passive thermally expandable elements, have been shown to enhance daylight penetration and reduce energy demand while limiting glare (ICONARP, 2020). In addition, experimental studies conducted in Algeria demonstrated that passive night ventilation combined with thermal mass in roofs could lower indoor temperatures by 6–10 °C during hot summer nights (Ben Cheikh & Bouchair, 2021).

4. Conclusion

This study examined the environmental performance of the Ziban Hotel, designed by Fernand Pouillon, by focusing on the luminous and thermal conditions of its most significant spatial sequence, the reception hall. Numerical simulations using Ecotect 5.5 and Radiance (2.0 Beta) provided a quantitative assessment of daylight availability, glare risk, indoor temperatures, and thermal comfort.

From a daylighting perspective, the hotel demonstrates notable strengths: well-oriented openings combined with movable shading devices contribute to a relatively uniform distribution of natural light, despite occasional episodes of glare. In contrast, thermal results indicate persistent overheating, with indoor operative temperatures often exceeding international comfort thresholds. While architectural strategies such as cross-ventilation, the presence of water features, and the use of reflective light-colored materials offer partial mitigation, they remain insufficient to maintain comfort during hot seasons without mechanical conditioning. These outcomes illustrate how Pouillon's architecture, conceived more than half a century ago, anticipated passive strategies that remain highly relevant to contemporary hot-climate design. At the same time, they underline the limitations of such strategies in the face of extreme climatic conditions.

The study also opens avenues for further research. On a theoretical level, it enriches the discussion on environmental comfort in modern architectural heritage within semi-arid regions. On a practical level, it informs current debates on the rehabilitation and adaptive reuse of heritage buildings, highlighting the need to combine conservation principles with contemporary sustainability standards. While the simulation focuses on a peak occupancy hour (4 PM), expanding the analysis to full-day and weekly variations would allow a more robust comfort evaluation. Further, a comparative investigation of Pouillon's hotels in different climatic contexts would further clarify the bioclimatic validity and adaptability of his architectural approach. Based on these findings, targeted retrofit strategies—such as low-SHGC glazing, controlled internal blinds and seasonal use of night ventilation—could significantly reduce overheating and glare risk while preserving architectural integrity.

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REPLICABLE SOLAR NEIGHBORHOODS: ENERGY EFFICIENCY AND MODULARITY AT THE URBAN SCALE IN THE ZEMCH CONTEXT

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ABSTRACT

This article presents a reflection on the application of the principles of the ZEMCH movement (Zero Energy Mass Custom Homes) at the urban scale through the design of modular, efficient, and replicable solar neighborhoods. The approach articulates mass customization, decentralized energy infrastructure, and urban sustainability as complementary pillars to address the challenges of energy transition in cities. Based on a qualitative and comparative methodology, three international case studies are analyzed—Fujisawa Sustainable Smart Town (Japan), The Sustainable City (United Arab Emirates), and Quartiere Violino (Italy)—which integrate photovoltaic energy into the urban fabric through adaptable modular solutions. The results indicate that early-stage energy planning, the adoption of replicable construction systems, and shared energy management significantly contribute to the development of resilient and low-carbon communities. It is concluded that solar neighborhoods designed according to ZEMCH principles can serve as strategic units for urban energy transition, adaptable to different cultural, climatic, and socioeconomic contexts.

Keywords: Solar neighborhoods; urban replicability; ZEMCH; photovoltaic energy; modular planning

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1. Introduction

Accelerated urban growth, the intensification of climate change, and the rising demand for energy have driven a global search for urban solutions that are simultaneously sustainable, resilient, and socially inclusive (IRENA, 2022). Cities of various scales face the challenge of providing adequate housing and efficient infrastructure while advancing toward the energy transition and meeting decarbonization goals. In this context, it becomes essential to rethink how urban space is planned, built, and operated, adopting integrated strategies that reconcile environmental performance, economic feasibility, and socio-spatial justice (Nejat et al., 2015).

Among the emerging approaches in this field, the concept of solar neighborhoods has gained prominence as a concrete and replicable solution (Singh, Hachem-Vermette & D'Almeida, 2023). These neighborhoods are designed with photovoltaic energy as a structuring element of both urban and architectural projects, incorporating distributed generation systems on rooftops, façades, and urban equipment. Their logic goes beyond the mere installation of solar panels on isolated buildings; it represents a model of urban organization in which the built environment functions as an active energy infrastructure, promoting self-sufficiency, energy security, and citizen participation (Lobaccaro, Frontini & Löfström, 2019).

In parallel, the ZEMCH (Zero Energy Mass Custom Homes) movement introduces a housing production approach focused on mass customization, modularity, light industrialization, and high energy performance. Although originally applied at the individual housing unit scale, the core principles of ZEMCH—such as replicability, climate adaptation, and accessibility—provide a robust conceptual foundation for scaling up to the neighborhood and urban fabric levels.

The convergence of these two approaches paves the way for the formulation of innovative urban models capable of combining technical efficiency and morphological diversity with social equity and environmental sustainability (Attoye et al., 2018). This article proposes an articulation between the principles of ZEMCH and solar neighborhoods as a strategic urban model for the energy transition in cities. Through a comparative analysis of three international case studies—Fujisawa Sustainable Smart Town (Japan), The Sustainable City (United Arab Emirates), and Quartiere Violino (Italy)—the study aims to identify replicable parameters of urban design, architectural modularity, and collective energy management applicable to different geographic and socioeconomic contexts. The central hypothesis is that solar neighborhoods planned according to ZEMCH principles can serve as urban energy transition units, integrating housing customization, environmental efficiency, and territorial scalability.

2. Methodology

This research adopts a **qualitative, exploratory, and comparative** approach to identify replicable urban strategies that combine decentralized energy planning, modular construction, and mass customization in line with the ZEMCH (Zero Energy Mass Custom Homes) principles. The objective is to derive design parameters applicable to diverse geographic and socioeconomic contexts, emphasizing energy transition and social sustainability.

The methodological process was structured into **three sequential stages**, summarized as follows:

2.1 Conceptual Review

An extensive review of scientific literature, technical reports, and policy documents was conducted to consolidate the theoretical foundations of solar neighborhoods, urban energy infrastructures, and housing production under the ZEMCH framework. Sources included international agencies such as IEA

SHC (2023) and IRENA (2022), as well as academic studies on modularity, replicability, energy efficiency, and light industrialization (Zomer et al., 2020; Singh et al., 2023).

2.2 Case Study Selection and Analysis

Three solar neighborhoods were selected based on their proven integration of photovoltaic energy into the urban fabric, their use of modular and customizable housing typologies, and their potential for replication in other contexts:

1. **Fujisawa Sustainable Smart Town** (Japan) – a smart city model emphasizing renewable energy, modular housing, and community-based governance.
2. **The Sustainable City** (United Arab Emirates) – a desert-based neighborhood achieving 100% local energy self-sufficiency through integrated PV infrastructure and climate-adaptive urbanism.
3. **Quartiere Violino** (Italy) – a social housing development applying modular grids, passive design strategies, and decentralized PV systems.

Each case was evaluated using **five analytical criteria**:

- Degree of solar energy integration in urban and architectural planning
- Modularity and customization potential of housing units
- Indicators of energy efficiency and environmental performance
- Management strategies and community engagement
- Technical, economic, and social replicability in other contexts

Where available, **quantitative indicators** were collected from official project reports, academic publications, and reputable technical sources. When exact figures were unavailable, estimates were made based on credible references, with clear indication of such assumptions.

2.3 Comparative Synthesis and ZEMCH Integration

A comparative matrix was developed to cross-reference the features of each case study with the core ZEMCH principles. This synthesis enabled the extraction of **replicable parameters** and highlighted both strengths and gaps in the analyzed projects. Special attention was given to the adaptability of these models to **Latin American urban realities**, particularly in regions facing rapid urbanization and energy vulnerability.

3. Results

The analysis of the three selected solar neighborhoods revealed a set of complementary strategies for energy and urban integration that align directly with the core principles of ZEMCH. Although implemented in distinct socioeconomic, climatic, and cultural contexts, the case studies share common structural elements: early-stage energy planning, modular construction, shared energy management, and territorial replicability potential. These characteristics reinforce the hypothesis that solar neighborhoods can function as urban energy transition units compatible with ZEMCH goals, expanding its scope beyond individual housing units.

3.1 Fujisawa Sustainable Smart Town (Japan)

Designed as a smart and sustainable city, Fujisawa SST represents one of the most advanced experiences in the application of photovoltaic energy at the urban scale. The project was developed through a consortium of private companies (led by Panasonic), local government, and residents, aiming to create an energy-autonomous and resilient community.

Each housing unit in the neighborhood is equipped with rooftop-integrated solar panels, battery storage systems, and digital monitoring platforms connected to collective energy management. The urban layout was carefully designed to optimize solar orientation, prioritize active mobility, and reduce the ecological footprint of the development.

- **Modularity and replication:** The houses follow adaptable modular construction patterns, allowing for morphological variations while maintaining cost control and efficiency.
- **Energy efficiency:** Studies indicate up to a 70% reduction in CO_2 emissions compared to conventional Japanese neighborhoods.
- **Community engagement:** Residents participate through digital platforms that display consumption and production data, encouraging energy awareness and responsible use.
- **ZEMCH compatibility:** Fujisawa embodies the principles of mass energy customization, with replicable and technically advanced solutions shaped by climatic and socio-technological criteria.

Figure 1: Fujisawa Sustainable Smart Town

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3.2 The Sustainable City (Dubai, United Arab Emirates)

Built in a desert region with extreme climatic conditions, The Sustainable City is a large-scale model of energy self-sufficiency, capable of generating 100% of the energy consumed by its residential buildings, commercial areas, and public spaces locally. The photovoltaic solution is distributed across large rooftop structures above streets, garages, and community facilities, forming a continuous solar collection grid.

The project also includes natural ventilation systems, climate-adapted green areas, electric mobility infrastructure, and local agro-food production—integrating energy, environment, and urbanism in a holistic manner.

- **Modularity and customization:** The residential units follow standardized typologies, with formal variations allowed based on solar exposure and residents' preferences.
- **Light industrialization:** Prefabricated elements were widely used, accelerating the construction process and reducing waste.
- **Shared energy management and redistribution:** The energy system operates as a local grid, with surpluses redirected for public lighting or electric vehicle charging.

- **ZEMCH compatibility:** The approach of adaptable standardization, combined with energy efficiency and self-management, demonstrates the feasibility of applying ZEMCH principles to medium- and large-scale neighborhoods.

Figure 2: The Sustainable City

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3.3 Quartiere Violino (Brescia, Italy)

Unlike the previous cases, Quartiere Violino stands out as a social housing initiative with decentralized energy infrastructure and a strong focus on replicability. Comprising 143 units (including single-story houses and low-rise buildings), the neighborhood features pitched roofs with optimized solar orientation and individual photovoltaic systems (~1.3 kWp per unit). The modular layout is clear and functional, facilitating the expansion of the model to similar contexts.

The orthogonal urban grid supports solar alignment of façades and encourages cross-ventilation, in addition to integrating green spaces and bike lanes. The neighborhood also incorporates principles of thermal passivity, such as solar conservatories and façade shading.

- **Simplicity and replicability:** The urban grid is based on a repeated modular pattern, easily adaptable to different plots and scales.
- **Thermal and energy performance:** The combination of solar capture, passive strategies, and low maintenance costs results in high environmental performance with economic viability.
- **Community energy education:** Residents have access to systems that monitor and display solar production, fostering a culture of energy efficiency.
- **ZEMCH compatibility:** The Italian experience shows that even social housing projects can adopt ZEMCH principles—particularly replicability, modularity, and energy self-sufficiency—with a focus on affordable contexts.

Figure 3: Quartiere Violino

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4. Conclusion and Future Work

The analysis of the three international case studies confirms that solar neighborhoods—when designed based on modularity, early-stage energy planning, and community participation—represent an effective urban strategy to expand the scope of ZEMCH (Zero Energy Mass Custom Homes) from the residential unit to the neighborhood and urban scale.

The convergence of housing customization, light industrialization, energy efficiency, and territorial replicability gives these developments a central role in building low-carbon, socially equitable, and technologically prepared cities for the energy transition. Projects such as Fujisawa, The Sustainable City, and Quartiere Violino demonstrate, in diverse contexts, that it is possible to transform the urban fabric into productive energy infrastructure with high environmental performance and strong replication potential. The combination of passive and active solutions, adaptable prefabrication, decentralized management, and community engagement provides a solid foundation for implementing more sustainable, resilient, and democratic urban models.

Furthermore, the studies show that applying ZEMCH principles at the urban scale does not require a rupture with local architectural paradigms, but rather their reinterpretation through clear technical guidelines: flexible modularity, operational efficiency, cost control, and distributed energy integration. This adaptation enables solar neighborhoods to become structural drivers of urban energy transition, contributing not only to emission reductions but also to the promotion of autonomy, energy security, and sovereignty in urban communities of varying socioeconomic profiles.

From a **policy perspective**, the replication of such models could be significantly accelerated through targeted incentives, regulatory frameworks for distributed generation, and integration of modular, high-performance housing standards into national and local housing programs. In emerging economies, particularly in Latin America, these initiatives could bridge the gap between climate targets and social housing needs, ensuring that low-income communities also benefit from technological innovation and energy independence.

Future work should focus on:

- The development of replicable design models based on climate, social, and energy performance parameters suited to Latin American contexts;
- The formulation of interdisciplinary guidelines involving urban planning, architecture, engineering, and public policy to incorporate ZEMCH principles into housing programs, especially those targeting social housing and resilient urban infrastructure;
- The creation of regulatory and financial instruments to support light industrialized construction, distributed generation, and shared energy metering, making technical customization viable without increasing final costs.

By strategically integrating architecture, energy, and territory, solar neighborhoods guided by the ZEMCH paradigm represent more than just a technical response to the climate crisis: they offer a concrete and structured alternative for the future of cities, aligning technological innovation, environmental stewardship, and urban regeneration.

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WATER AS A REACTIVATION SOURCE OF HERITAGE ATMOSPHERES: MICROCLIMATIC CHARACTERIZATION OF THE ROMAN BASINS' URBAN SQUARE IN GAFSA (SOUTH TUNISIA)

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ABSTRACT

Adopting a microclimatic approach, this research investigates the environmental challenges faced by the Roman basins' square, a historic urban public space in Gafsa city (southern Tunisia). As an ancient heritage site inserted into a vernacular urban fabric (Medina), this square constitutes an interesting example of a heritage urban space where urban forms, uses, and climatic factors dynamically intersect. The study is based on the analysis of in situ collected data including several physical parameters (temperature, humidity, sunshine, wind). These parameters constitute the physical environmental signals that mainly characterize this urban square's ambience. It aims to provide a detailed characterization of microclimatic environments while highlighting the structuring role of the presence of water in the thermal regulation of the site. The outcomes reveal the existence of micro-spaces with high bioclimatic potential, resulting from the interaction between morphology, vegetation and water systems. By highlighting the cooling effect of the Roman pools, this research demonstrates that water can be a factor for the sensorial and sustainable redevelopment of historic centers facing climate challenges. It invites us to recognize heritage environments as levers of adaptation, where memory, comfort, and sustainability come together in a contextualized project.

Keywords: Heritage ambiences, Urban microclimate, Historic urban public space, Water system, Sustainable requalification.

1. Introduction

Outdoor spaces constitute main components of urban life due to their role in hosting community activities and shaping the city's image. In Mediterranean, Saharan, continental, and/or temperate contexts, the configuration of these urban spaces also responds to environmental constraints and creates sensory qualities specific to each territory. In fact, in cities in southern Iran or Turkey, public squares and gardens are designed to integrate water, vegetation, and shade as resources for thermal comfort and conviviality. Similar Roman basins integrated within urban fabrics can be found across the territories of the Roman Empire, such as in Umm El-Jimal in Jordan, illustrating the wide geographical extent and enduring legacy of these hydraulic systems. From a theoretical point of view, the urban planning specialists consider public space not as a simple functional surface, but rather as a lived and shared place, carrying atmosphere and memory (Lynch, 1998; Gehl, 2011; Alexander et al., 1977). Despite the current changes that our cities are experiencing, some of their historic urban spaces resist the vagaries of time and remain sensitive landmarks carrying urban and social memory while confronting the spatial, functional and environmental transformations they undergo. Their survival can only be ensured if we rethink their adaptation to contemporary changes while preserving their environmental specificities. It is within the framework that this contribution focuses specifically on a southern Tunisian historical urban space and highlights the environmental, sensory, and social issues that prevail within.

2. The survival of historic urban spaces: The environmental concerns

Nowadays, historically resilient urban spaces appear marginalized and detached from their original environmental logic. This situation, recorded in Tunisia, is common in many Maghreb, North Africa, and Middle Eastern cities. In this context, the sustainability of these historic centers cannot be reduced to rigid restoration or simple conservation, nor can they become inert museum heritage. Instead, it requires a sensory-based, continuous reassessment of their physical environment (Monshizade, 2008; Mahroug, 2017; Belakehal, 2024). Thinking about their survival means questioning their potential to generate specific ambiences that ensure quality public spaces while responding to contemporary environmental constraints such as global warming, urban heat islands, and water scarcity. The ambient approach offers a valuable framework for analyzing these spaces as living environments shaped by perceptions, memories, and climatic dynamics, rather than as static heritage objects.

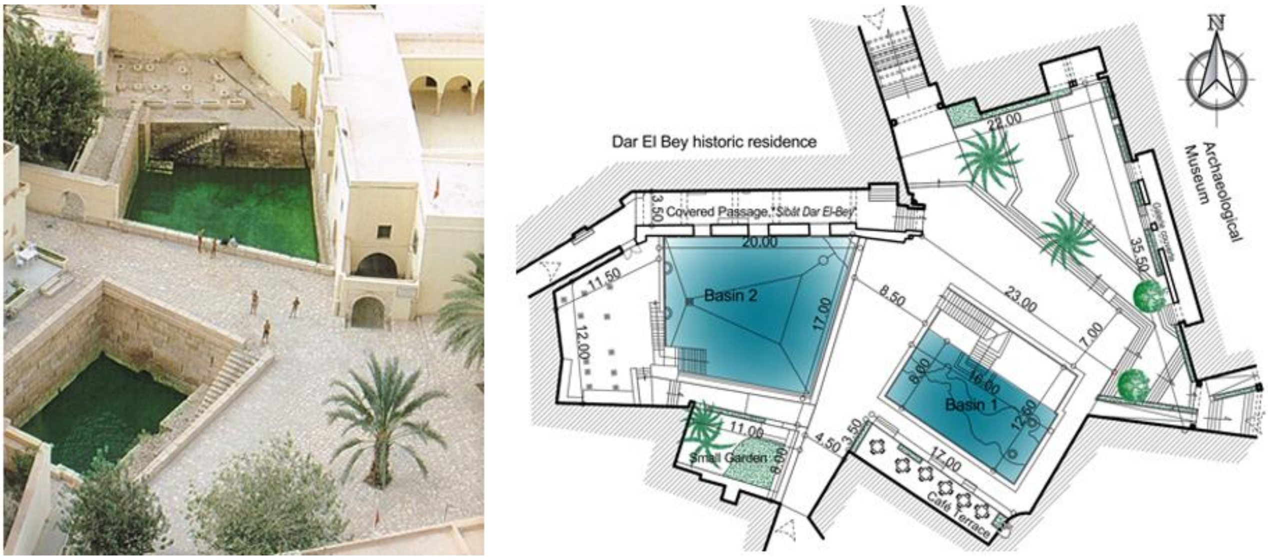
3. The heritage ambience: conceptualization and operationalization

Within urban and architectural spaces, ambience emerges from the sensory interaction between physical stimuli and users. The ambient approach highlights these relationships, linking the physical signals, spatial configurations, and perceptive experiences of individuals (Belakehal et al., 2009; Belakehal, 2013). Applied to heritage sites, this approach gains complexity as such places carry sensitives spatio-temporal layers requiring interdisciplinary methods – modelling, virtual restitution or content analysis – to understand how they were and are experienced (Belakehal, 2012; Belakehal, 2024). In this contribution, the focus narrows to physical environmental signals – climatic factors, water and vegetation– whose interaction shapes the microclimatic and sensory qualities of the Roman basins square. This lens enables a contextualized reading of the site's ambiance as lived today, providing insights for its sensitive and sustainable requalification (Zid, 2022).

4. The Roman Basins Square in Gafsa

Located in the heart of Gafsa's medina-oasis in southwest Tunisia, the Roman basins square is a central heritage site built on the remains of the ancient Numido-Roman city of Capsa (Khannoussi and Ayachi, 2012) (Figure 1).

Figure 1: Aerial views of the Roman Basins Square.



Font: Abdelkefi (2009, p. 224); The authors.

Organized around a water system dating back to the 2nd century, the basins once captured and venerated the city's main water source (Trousset, 2012). Historical accounts highlight their multiple functions – irrigation of the oasis, drinking water supply, public hygiene – as well as the thermal nature of the springs that once fed them. Until the mid-19th century, the Roman basins largely preserved their medieval character, with water flowing by gravity through a vaulted underground gallery. Listed as a national heritage since 1915, they reflect a long-standing tradition of water management in the oasis towns of southern Tunisia. However, the 20th century brought major spatial, environmental, and social transformations. The drying up of the natural springs in the late 1990s and occasional artificial refills have altered both the site's water regime and its sensory atmosphere, often perceived by residents as a "loss of soul" (Zid, 2022; Zid et al., 2024b). Despite these changes, the Roman basins remain a social and cultural landmark, preserving their role as a gathering place around water (Zid, et al. 2021; Zid, et al. 2024a). Their requalification requires approaches that combine microclimatic potential, sensory values, and sustainable urban redevelopment strategies.

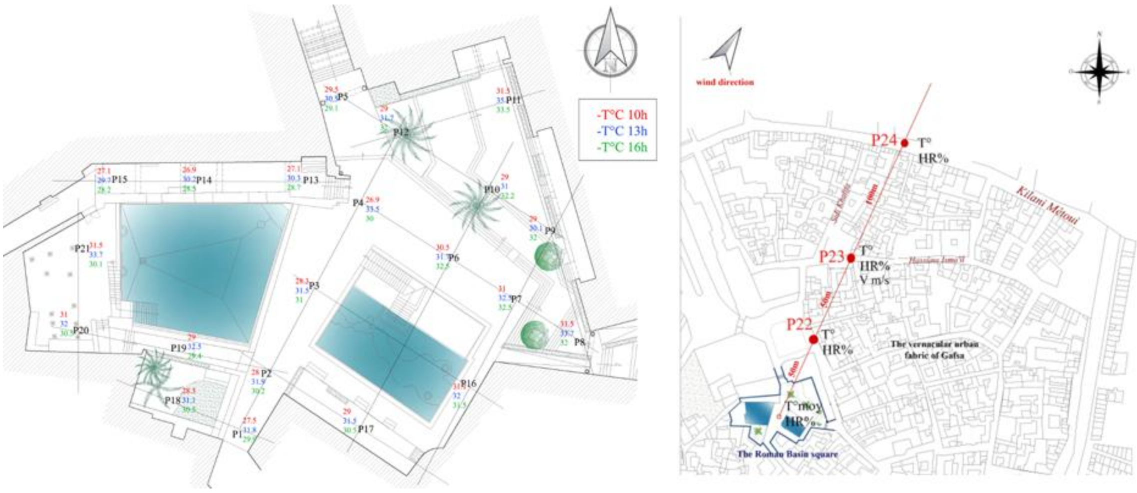
5. Methodology

Building on previous studies exploring relationships between urban morphology and microclimate parameters (Gandemer, 1976; Grouleau, 1986; Oke and Nakamura, 1988; Nishimura et al., 1998; Nikolopulou et al., 2001; Athamena, 2012; Monshizade, 2012; Xue et al, 2015), this research investigates how the presence or absence of water affects thermal comfort and perceived atmosphere in a hot, arid historical context. A physical approach combining in situ measurements and spatial analysis was adopted. Main parameters – air temperature, relative humidity, wind speed and direction, and sunshine conditions – were recorded using portable instruments (thermo-hygrometer and anemometer) along a mobile route adapted to the irregular morphology of the square. A preliminary campaign conducted on 12 May at 10 a.m., 1 p.m., and 4 p.m. (Figures 2-3) identified 24 measurement points, capturing both microclimatic variations and solar exposure patterns. Results revealed temperature differences up to 4°C between shaded and exposed areas, as well as stable airflows in certain zones. These findings informed the protocol for the final measurement campaign. This combined *mobile–experimental* approach allowed for a fine-scale characterization of the interactions between water, space, and climate while remaining adaptable to the site's complex morphology. It provides a transferable tool for studying other heritage contexts facing similar climate challenges.

Figure 2: Preliminary measurement tests in the Roman Basins Square, May 12.

Font: The authors.

Figure 3: Location of measurement points.



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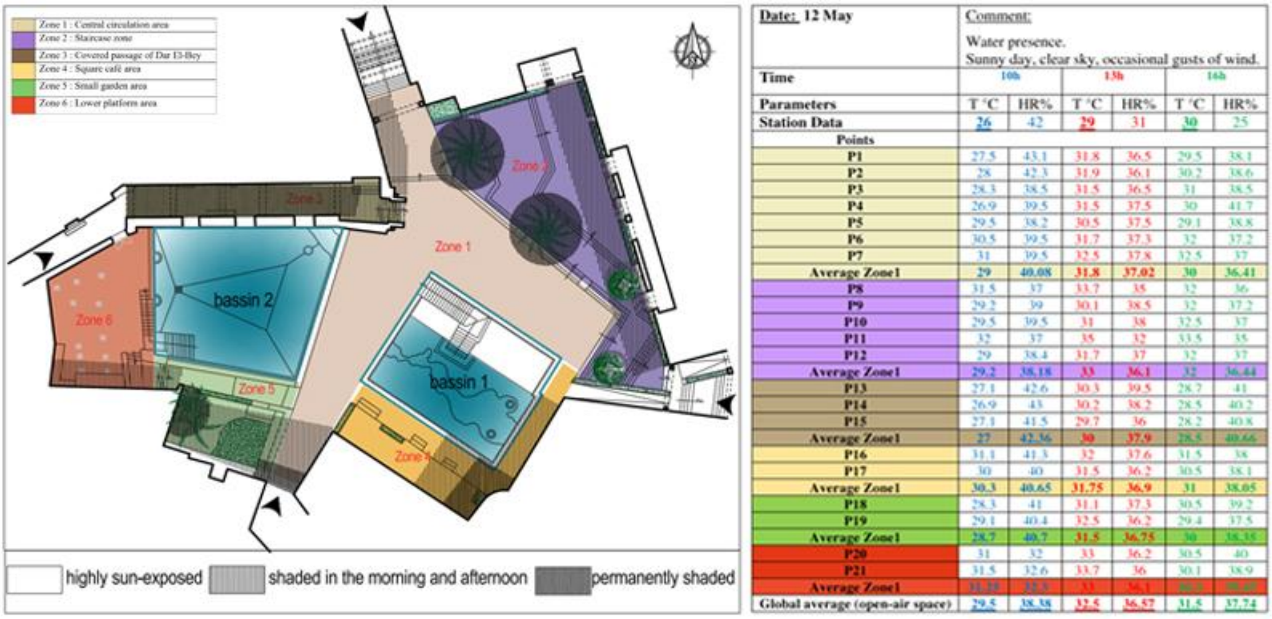
6. Results: Microclimatic Characterization of the Roman Basins Square

In this compact urban fabric under a hot and arid climate, the square shows strong solar exposure, especially between April and October. The museum steps area, elevated and sparsely vegetated, emerges as the hottest and driest zone, whereas the Dar El-Bey covered passageway and the southern small garden remain the most temperate, benefiting from stable shade, higher humidity, and wind protection (Figure 4).

Figure 4: Thermal and climatic zoning of the Roman Basins Square.

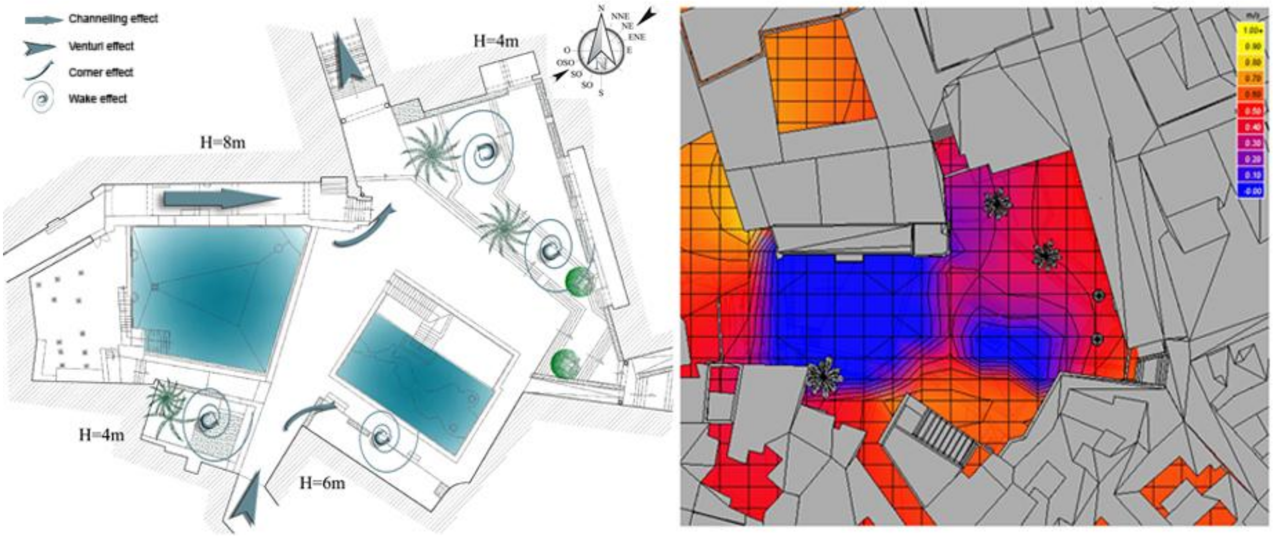


Date: 12 May	Comment: Water presence. Sunny day, clear sky, occasional gusts of wind.					
Time	10h		13h		16h	
Parameters	T °C	HR%	T °C	HR%	T °C	HR%
Station Data	26	42	29	31	30	25
Points						
P1	27.5	43.1	31.8	36.5	29.5	38.1
P2	28	42.3	31.9	36.1	30.2	38.6
P3	28.3	38.5	31.5	36.5	31	38.5
P4	26.9	39.5	31.5	37.5	30	41.7
P5	29.5	38.2	30.5	37.5	29.1	38.8
P6	30.5	39.5	31.7	37.3	32	37.2
P7	31	39.5	32.5	37.8	32.5	37
Average Zone1	29	40.08	31.8	37.02	30	36.41
P8	31.5	37	33.7	35	32	36
P9	29.2	39	30.1	38.5	32	37.2
P10	29.5	39.5	31	38	32.5	37
P11	32	37	35	32	33.5	35
P12	29	38.4	31.7	37	32	37
Average Zone1	29.2	38.18	33	36.1	32	36.44
P13	27.1	42.6	30.3	39.5	28.7	41
P14	26.9	43	30.2	38.2	28.5	40.2
P15	27.1	41.5	29.7	36	28.2	40.8
Average Zone1	27	42.36	30	37.9	28.5	40.66
P16	31.1	41.3	32	37.6	31.5	38
P17	30	40	31.5	36.2	30.5	38.1
Average Zone1	30.3	40.65	31.75	36.9	31	38.05
P18	28.3	41	31.1	37.3	30.5	39.2
P19	29.1	40.4	32.5	36.2	29.4	37.5
Average Zone1	28.7	40.7	31.5	36.75	30	38.35
P20	31	32	33	36.2	30.5	40
P21	31.5	32.6	33.7	36	30.1	38.9
Average Zone1	31.25	32.3	33	36.1	30.3	39.45
Global average (open-air space)	29.5	38.38	32.5	36.57	31.5	37.74

Font: The authors.

The analysis of wind dynamics confirms the role of morphology in shaping the ambient quality: channeling effects in covered passages, Venturi effects at access points, stagnation pockets in enclosed areas, and airflow corridors in open breakthroughs (Figure 5). Cross-referencing wind patterns with temperature and humidity data helped identify micro-spaces with either improved comfort or thermal stress (Brouillet, 2020). The presence of water plays a central role: measurements revealed an average air temperature drop of 2°C and a 3% increase in relative humidity near the pools when filled, attributed to evaporation under direct sunlight. At the square scale, areas close to water and shaded green zones thus exhibit greater thermal comfort and higher microclimatic stability, with relatively homogeneous values within each zone.

Figure 5: Aeraulic effects in the Roman Basins Square.



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7. Discussion: From heritage ambiances to climate-responsive design

The results confirm the structuring role of spatial configuration and the thermal regulating effect of the Roman basins in shaping the microclimatic and sensory quality of Gafsa's historic square. By mapping temperature, humidity, shade, and airflow, the study identified zones of comfort and thermal stress, showing how water, vegetation, and morphology interact to create microclimatic ambiences. Beyond the local scale, these findings resonate with other historic and contemporary water-based projects. Such in Tiznit (Morocco), the “Blue Source” project combines heritage restoration, ecological rehabilitation, and public space design around a sacred spring, reinforcing social identity and urban memory (Naji et al., 2016). In Europe, projects such as Marseille 2013 or the urban fountains of Chartres illustrate how water features, dry fountains, and misting systems contribute to urban cooling, sensory experiences, and social interaction (Latarjet, 2010). Similarly, parks in Marktredwitz (Germany) integrate playful water elements for a tactile and recreational experience (Geisel, 2011). Such examples highlight how historic water heritage can inspire modern “aquatic urban landscaping,” merging climate adaptation with cultural revitalization. In Tunisia and other arid regions, these insights could guide architects and planners to reintroduce water elements in heritage squares or new urban developments, not only for thermal comfort but also for social and cultural value. Besides, complementary research on visitor perceptions confirms the persistence of sensory relationships with the Roman basins, similar to those described by past travelers. This enduring “inter-sensory connection” to the basins—centered on water—remains rooted in local memory. Inhabitants continue to gather around the pools to refresh themselves, socialize, and celebrate shared cultural practices. These activities, imbued with historical and symbolic values, demonstrate the durability of ambiences that transcend eras and reinforce the heritage dimension of the site (Zid et al., 2024b).

8. Conclusion

This study highlights the relevance of an ambient approach to historic public spaces in hot and arid contexts. The microclimatic analysis of Gafsa’s Roman Basins Square demonstrates how water, combined with morphology and vegetation, generates micro-spaces of improved thermal comfort, linking environmental performance with the sensory and cultural memory of the site. Beyond Gafsa, these findings open perspectives for climate-responsive urban design, showing how heritage water systems can inspire sustainable and culturally rooted strategies for revitalizing historic centers.

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ADOPTION OF ARTIFICIAL INTELLIGENCE IN CONTEMPORARY ARCHITECTURAL PRACTICE: EXPLORING KNOWLEDGE, USE, AND BARRIERS AMONG PRACTICING ARCHITECTS

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ABSTRACT

This study investigates the state of Artificial Intelligence (AI) integration within architectural practice by surveying a diverse sample of practicing architects in the United Arab Emirates. The aim is to explore practitioners' knowledge, tools, and engagement with AI, as well as their perceptions regarding its future potential and the barriers hindering its broader adoption. The research builds on a structured survey targeting various generational cohorts, educational backgrounds, and professional contexts, with responses collected from 52 practicing architects. The questionnaire addresses four key themes: (1) professional and demographic background, (2) digital tools in current use, (3) current and anticipated use of AI in design tasks, and (4) challenges and support mechanisms required for AI integration. The findings contribute to a clearer understanding of the architecture industry's readiness for digital transformation and offer insights into strategic entry points for AI training, policy support, and tool development. By mapping current practices and attitudes, this research informs the discourse on AI's role in shaping the future of architecture, while highlighting the socio-technical and institutional gaps that must be addressed. The implications extend to educators, policymakers, and software developers aiming to align AI capabilities with industry needs.

Keywords: Artificial Intelligence in Architecture; Architectural Design; Architects' Perceptions; AI Adoption Barriers; Architectural Practice in UAE

1. Introduction

Artificial Intelligence (AI) has spread into every aspect of life due to its great potential to increase efficiency and quality in performing different tasks. Architectural design is no exception, especially with remarkable advances achieved in generative AI models (Ploennigs & Berger, 2023). Generative AI capabilities unlock great potential in supporting designers in transforming ideas to 2D and 3D images/renders (Fernberg & Chamberlain, 2023). AI uses generative machine learning models/algorithms, especially text-to-image generative models, to generate different forms of architectural designs and renders (Brown et al., 2020). Generative AI models are trained using large data sets that can be in the form of images, text, and architectural drawings (Yuan et al., 2025). The size and quality of the data sets influence the accuracy, and the quality of the AI model outputs (Whang et al., 2023). Many architecture-focused AI tools/websites have been launched in recent years; however, few have proven useful in practice due to issues related to accuracy, sensitivity to context, and affordability. Having an AI model/tool that can produce designs/renders with a high level of accuracy and resolution would be of great utility for architects (Yildirim, 2022).

Architects typically perform building design in phases. Each phase involves different tasks that are commonly multidisciplinary and complex (Hettithanthri et al., 2023). For example, data collection and analysis are essential steps that architects perform throughout the design process. Architects typically gather data about client requirements, code and standards requirements, and similar case studies/designs to perform design tasks. They typically handle large amounts of data, especially in the early design phases that are, sometimes, challenging to process. AI could make these tasks easier and substantially shorten the time used to perform them (Amer, 2023; Yuan et al., 2025). In addition to data processing, architects create conceptual designs that are prepared for obtaining client approval on the design. These conceptual designs contain schematic floor plans, elevation and 3D models and renders. Architects typically have limited time to perform these tasks (a few hours to a few days). AI can become a game changer if developed to the level that can substantially support this process. However, AI is yet to be adopted or utilized to its full potential by the architectural design industry due to reasons that we are trying to explore in this study.

Despite mounting interest in AI-driven design, empirical research from the Middle East regarding real-world implementation, practitioner attitudes, and context-specific challenges is scarce. This study stands out as it bridges this gap through the systematic mapping of the readiness of the UAE architecture sector for digital transformation, drawing on first-hand practitioner input. This study is the first step of a larger study that aims at developing an AI tool that can generate designs/renders that are context sensitive

To this end, this study aims to: (1) explore the status of AI usage/applications in the architectural design practice field, (2) identify the barriers and challenges to further implementation, and (3) develop recommendations for advancing the use of AI in architectural design in a way that increase efficiency and improves the quality of design outputs.

2. Methodology

A sixteen (16) question survey was designed for the purpose of capturing the status of AI use within the architectural design practice in the UAE. The questions were classified under four (4) different sections: (1) participant background Information (e.g., education, and role in the design team), (2) AI in practice, (3) Perceptions and outlook, and (4) challenges and barriers that delay further adoption of AI in architectural design. This classification was intended to capture the possible correlation between AI usage in architecture and the different categories of the survey in addition to identifying the possible barriers and challenges facing further implementation. The survey recruitment took place through social media such as LinkedIn and authors' professional network. Responses were collected over a two-week period (June 25th until July 10th, 2025). The survey was created using google forms and a QR code was generated to ease survey sharing and distribution. The participants were allowed to choose more than one answer in most of the questions in addition to the option of adding their own answer under "other" option. Ethical approval for this study was obtained from the Research Ethics Committee of the United Arab Emirates University (Approval No. ERSC_2025_7724). Participation was voluntary, and informed consent was obtained from all respondents.

3. Results and discussion

Fifty-two (52) responses were received for the survey. Based on the survey results, the educational background of the survey participants was found to be ~ 90% with a degree in architecture while the remaining ~10% have degrees in closely related fields such as interior design and engineering. Figure 1 demonstrates the various tasks that are typically performed by the survey participants including building design (~30% of the participants), design and building detailing (~75% of the participants), project management (~46% of the participants), and building permits (~12% of the participants). These responses indicate that a large number of participants are involved in several tasks throughout the building design and detailing process.

Figure 1: Participants role in projects team

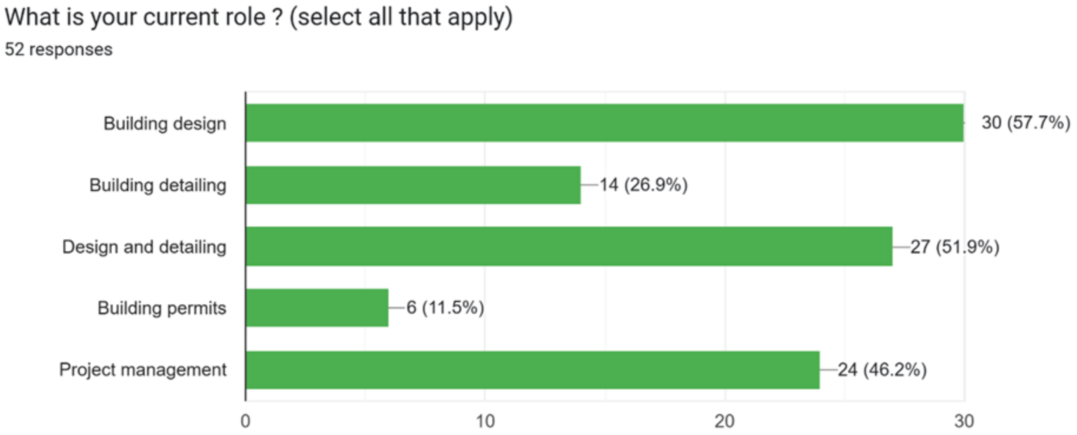
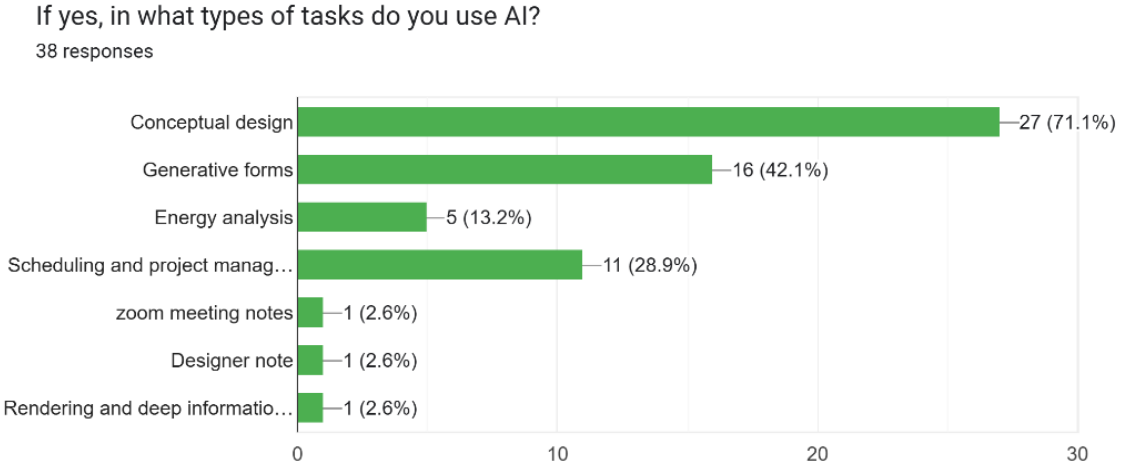


Figure 2: Tasks performed using AI



In their response to whether the participants use AI to perform tasks related to their duties, ~70% of the participants indicated that they use it. While ~30% of participants indicated the contrary. This result provides an overall indication that AI has infiltrated into the field of architecture. However, a relatively large portion of participants (~30%) are hesitant to use it for various reasons that will be discussed later in this paper. Figure 2 shows the different tasks participants use AI. About 60% of participants indicated that they use AI in the early design stages in tasks related to conceptual design. While ~ 40% of participants indicated that they use AI in generating 3D forms. 13% of participants indicated that they use AI in energy analysis, and about 29% of participants demonstrated that they use it in tasks related to project management and scheduling. A slight portion of participants (~7.5%) showed that they use AI in other tasks such as recording online meeting notes, and designer notes. The findings in Figure 2 are evident that AI is largely used in conceptual design phase to support the development of design concept and initial schematic design.

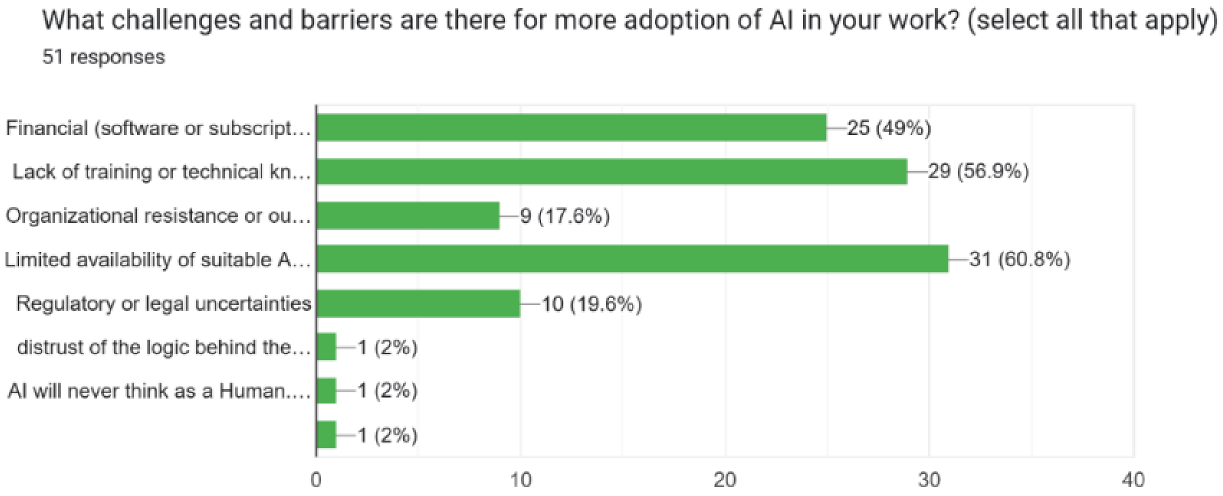
The results also show that about 83% of participants are willing to use AI further in performing their design tasks. However, ~10% of participants were against increasing usage of AI in their professional context while ~8% were not sure whether they should be using AI further on not. Overall, the findings demonstrate that a substantial percentage of practitioners are interested in further usage of AI. These findings necessitate the need to further develop AI tools to enhance their performance and accessibility. The participants who are not interested in using AI further were given the option to state the reason. Table 1 lists their responses in this field. The responses highlighted the perception that AI would replace human architects as can be seen in statements 1-8. Another reason that was listed by participants of not being interested in AI is that they think it increases laziness and reduces human creativity as they become dependent on it (Table 1 statements 3,5,7, and 8).

Table 1: Participants' opinion on why they are not interested in using AI further in performing their work

	Why do you not want to use AI further in your work, including architectural design?
1.	Human touch is still important in design
2.	It's not clear and realistic
3.	I have never found an AI software that is advanced enough to be worth the time I could be doing the task myself. Maybe in the future if they are more advanced and more intelligent, I might consider using them. But even then, I wouldn't use them for any creative tasks, only routine tasks.
4.	I am happy to do my own thinking
5.	It reduces the capability to think and developed skills
6.	AI is for people with no knowledge.
7.	The more AI involves in professions, the less the need for human intelligence.
8.	Because if we depend solely on AI our brains would rely on it, and we would be weak in certain aspects as well as lazy

On another front, participants were asked what they wish to see developed or integrated in AI tools/models. The responses were grouped under nine categories shown in Table 2. Participants highlighted the need to enhance AI capabilities to include production of 2D drawings, more accurate 3D models, design review functions, performance analysis, and urban design support. Feedback on improving AI capabilities shows a clear focus on increasing efficiency and saving time by enabling AI tools to perform time-consuming tasks such as design detailing, modification, and performance analysis. Participants also emphasized expanding capabilities to include new domains like virtual walkthroughs and handling projects at the urban scale. Participants were asked to identify the challenges and barriers to AI adoption (Figure 3) and the support and resources needed to overcome them (Figure 4). The top challenges cited were the limited availability of suitable AI tools (~60%), lack of training and technical knowledge (~57%), and limited financial resources (~50%). In terms of support required, participants prioritized financial resources (~40%), training (~65%), and better AI tool capabilities (~75%).

Figure 3: Challenges and barriers for more adoption of AI in architectural practice



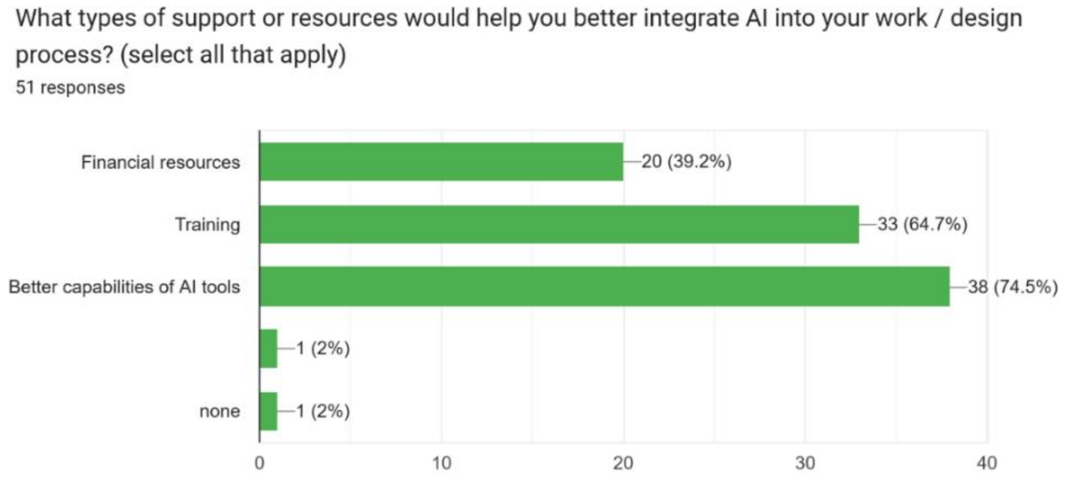
These findings emphasize the need to further develop current AI tools and introduce new ones aligned with industry needs. They also underline the importance of enhancing architects' technical skills through targeted training and integration of AI content into architectural curricula. Lastly, participants stressed improving the affordability of AI tools—such as lowering subscription fees—to enable wider access and practical application.

Table 2: Participants' opinion on what capabilities they would like to have in AI tools

Aspect	Participants AI capabilities wish list
Conceptual design	"Inspiration of development the concept and landscape and help in render"; "Enhancing design alternative solutions- enhancing design concept- generate elevation and layout design alternatives".
2D drawings	"Produce plans and drawings; Draw the building in AutoCAD"; "To create detail drawings"; "save me more time with creating fixed templates";
Accuracy	"Preform more accurately and generate the same design in different side views"; "It's easy to use and provide information faster and accurately".
3D modeling	"3D presentation; 3D video resolutions"; "Seeing 3D instantly come to life by just giving sketches and plans to an AI website"; "Quick massing or schematic design suggestions based on client input or site constraints to speed up early-stage design"; "Helping create interactive visualizations or immersive walkthroughs to better communicate design intent to non-technical clients".
Design review	"Review the design and tell me weak points"; "Review the design based on healthcare standards"; "Check mistakes and give options"; "Assist the follow up in the work performance"; "For floor plans and rectifying client comments with building rules"; "Fast modification of material and color in rendering".
Interior design	"Options for equipment layouts"; "Furniture – interior"
Performance analysis and simulation	"Lighting analysis"; "AI could do complicated simulations to save time and effort, also visualizing processes of concept".
Urban design	"Urban Design as well"; "Detail design of urban scale projects".
Document control and task	"Act as an assistant that manages daily tasks, arranging emails, documentation, keep things ready for me to have better decisions".

management

Figure 4: Resources and support required to advance AI use in architectural practice



4. Conclusions

In this paper, the status of AI integration in the architectural design practice in the UAE was explored. The study surveyed 52 practicing architects and engineers who are directly involved in architectural design. The findings indicated the willingness of the industry to integrate AI tools/models in practice. However, the findings indicated the need to overcome several challenges and barriers that hinder advancing AI applications.Notably, the findings indicated the need for technical training of professionals on the use of AI, deploying more financial resources and improving the existing AI tools to fit various contexts and to include broader functionalities. Charting the current landscape, practitioner attitudes, and barriers to adoption, this study offers a strategic roadmap to the future of AI integration in the UAE's architectural industry, a more innovative, competitive, and contextually responsive built environment. These conclusions have wider applicability to fast-developing regions adopting digital transformation in architecture. The authors do acknowledge some limitations of the study such as the limited survey sample size (52 participants) and the region-specific applicability of results as the targeted sample survey are all practicing architects in the UAE.

Acknowledgements:

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REIMAGINING SOCIALLY SUSTAINABLE MOBILITY: COMMUNITY-DRIVEN VR PROTOTYPES FOR ADAPTIVE URBAN NETWORKS IN AL AIN CITY

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ABSTRACT

As Al Ain undergoes a major transformation in its transportation system, shifting from roundabouts to signalized intersections, this research reimagines mobility through a socially sustainable and community-driven lens. Moving beyond technical efficiency, the study proposes intersection prototypes that prioritize human experience, equity, and cultural continuity within the city's evolving urban network. In addition to a community survey, which captures perceptions and priorities regarding mobility and urban spaces, Virtual Reality (VR) is employed as a design and as a medium for participatory engagement. Together, allowing residents and stakeholders to visualize, evaluate, and contribute to mobility solutions, ensuring that design responses are grounded in local needs, promote inclusivity, and enhance social cohesion. The prototypes integrate shaded pedestrian routes, green infrastructure, and context-sensitive open spaces that encourage walkability, improve microclimatic conditions, and strengthen everyday community interactions. Heritage landmarks and traditional architectural motifs are incorporated to anchor cultural identity while advancing contemporary sustainable goals. By reframing intersection design as a catalyst for repurposing urban space and enhancing community connectivity, the study highlights how adaptive, VR-supported planning can deliver mobility solutions that are environmentally responsive, socially inclusive, and culturally grounded. The findings contribute to broader debates on resilient urban futures, where infrastructures serve to facilitate movement, enhance livability, belonging, and community well-being.

Keywords: Social Sustainability; Community-Driven Urban Networks; Virtual Reality (VR); Urban Space; Al Ain.

1. Introduction

Urban mobility is not only about movement, but also fundamentally about shaping the quality of everyday life in cities. Transport systems influence how people access opportunities, experience public space, and construct a sense of belonging, identity, and equity. In rapidly urbanizing contexts, however, mobility planning has been dominated by technocratic approaches that emphasize efficiency, flow management, and vehicular throughput. While such strategies may optimize circulation, they often neglect the equally crucial social and cultural dimensions of sustainability, resulting in infrastructures that function mechanically but fail to support inclusivity, social cohesion, or cultural continuity (Banister, 2008)

At the global scale, policy frameworks such as the United Nations Sustainable Development Goals (SDGs) have called for a paradigm shift toward mobility solutions that balance environmental responsibility with social sustainability, health, and heritage preservation (United Nations, 2015). This shift recognizes that roads and intersections are not neutral technical objects; instead, they structure how public life unfolds, how cultural identity is reinforced, and how communities connect across space. Scholars and practitioners have increasingly emphasized concepts such as walkability, human-centered design, and participatory planning as essential tools for ensuring that mobility infrastructures contribute to livability and inclusivity, rather than detracting from them (Dovey & Pafka, 2020).

In this discourse, intersections occupy a critical role. Traditionally conceived as nodes that regulate traffic, intersections also serve as urban thresholds where mobility, social interaction, and spatial identity converge. They can either act as barriers that fragment communities or as catalysts that generate public life, cultural exchange, and everyday encounters. Designing intersections through a socially sustainable lens requires integrating features such as shaded walkways, safe pedestrian crossings, public seating, and culturally sensitive design elements that reinforce a city's identity. When approached in this way, intersections become more than mobility devices; they become civic spaces that mediate between heritage and modernity (Gill et al., 2013).

Emerging technologies, particularly Virtual Reality (VR), further expand the possibilities of reimagining mobility. VR allows planners, decision-makers, and residents to immerse themselves in proposed designs before they are realized, providing a powerful platform for participatory engagement (Portman et al., 2015). By enabling stakeholders to "walk through" alternative scenarios, VR helps communities to articulate their preferences, identify shortcomings, and co-create solutions that align with local values. Beyond being a visualization tool, VR becomes a medium of dialogue, bridging technical expertise with lived experience, and future scenarios with cultural memory (Howard & Gaborit, 2007).

Human-centered urban design theory prioritizes the lived experience of city dwellers – a tradition going back to thinkers like Kevin Lynch (1960), who studied how people perceive and mentally map cities. VR offers a novel way to extend this tradition by experimentally placing users inside simulated urban environments, which allows researchers and designers to gauge human responses to design alternatives in a controlled yet realistic setting. For instance, Kim & Kim (2019) employed immersive VR simulations to test an urban design principle (the optimal building height-to-street width ratio in public squares). Participants' preferences in the VR environment provided evidence to validate (or challenge) conventional design rules, underlining VR's value for user-centered design experimentation. Sensory immersion and behavior: One advantage of VR is the ability to engage multiple senses, aligning with environment-behavior theories that stress how sensory cues affect urban experience. Sánchez et al. (2017) demonstrated this by using VR with spatial audio to study how traffic noise influences the comfort of an urban square; the immersive audio-visual simulation helped isolate noise as a factor in public space preference. Similarly, Maffei et al. (2016) found that a congruent mix of virtual sound and visuals yields more reliable community feedback on proposed developments, as participants respond to the holistic atmosphere of a place rather than just abstract plans. These studies build on human-centered design frameworks by treating the city as it is experienced through VR – capturing subtle reactions like emotional mood, sense of safety, or comfort. Notably, recent experiments report that VR can generate strong emotional engagement and attention to detail. In a 2024 Frontiers in VR study, observers using 360°-video VR of neighborhood parks not only noticed fine-grained information (e.g., materials, lighting) but also expressed personal feelings about the space ("unwelcoming" vs. "inviting"), indicating a high level of immersion and realism in their experience. This emotional and cognitive feedback is invaluable for human-centered design, which seeks to understand users' needs and feelings in context.

Gordon, Schirra & Hollander (2011) introduced the concept of "Immersive Planning", a model for integrating new technologies (like VR) into public participation to deepen engagement. Earlier, Hanzl (2007) had reviewed ICT in planning, foreshadowing VR's potential. More recently, Piga et al. (2021) developed a conceptual framework for smart co-design, using AR/VR apps to support collaborative urban planning. These works provide a theoretical scaffolding, suggesting that VR's immersiveness can foster greater empathy, creativity, and consensus-building among participants than traditional methods.

Recent scholarly studies: Over the last decade, empirical research has validated these theoretical expectations. For example, Meenar et al. (2020) used multi-sensory immersive VR in public workshops and found higher levels of participation and feedback quality compared to traditional presentations. Participants in VR-based sessions demonstrated better memory recall of proposed scenarios and stronger emotional responses, indicating deeper engagement. In a similar vein, van Leeuwen et al. (2018) reported that introducing VR in a municipal park redesign process heightened public enthusiasm and co-design involvement, ultimately improving the final design outcomes. Case studies by Stauskis (2014) in Vilnius and Schrom-Feiertag et al. (2020) in Vienna have shown that VR and AR can increase transparency, inclusivity, and the efficiency of participatory planning by immersing citizens in proposed changes. The literature suggests VR aligns well with participatory planning theory: it operationalizes abstract ideas of empowerment and collaboration into interactive urban experiences.

Al Ain City provides a timely and relevant context for exploring these questions. As part of a major transportation transition, Al Ain Municipality is replacing its iconic roundabouts—once symbolic of the city's greenery and identity- with signalized intersections. While this transformation is expected to enhance traffic efficiency and safety, it raises pressing concerns about its broader social and cultural repercussions. Roundabouts in Al Ain have historically served as more than just traffic regulators; they have also been landscaped green spaces that contribute to the city's microclimate, imageability, and tourism appeal. Their removal risks not only diminishing environmental quality but also eroding the symbolic urban fabric that underpins community identity and cohesion.

To examine how such transformations can be reframed as opportunities for social sustainability rather than losses, this study adopts a mixed-method approach that combines community surveys with VR-based participatory workshops. The survey captures residents' priorities regarding walkability, adaptive reuse, cultural tourism, and the quality of public space, providing a grounded understanding of community aspirations. Meanwhile, the VR scenarios allow both experts and residents to evaluate and interact with alternative intersection prototypes—on-ground, elevated, and underground—illustrating how different design choices affect mobility, safety, cultural identity, and everyday livability.

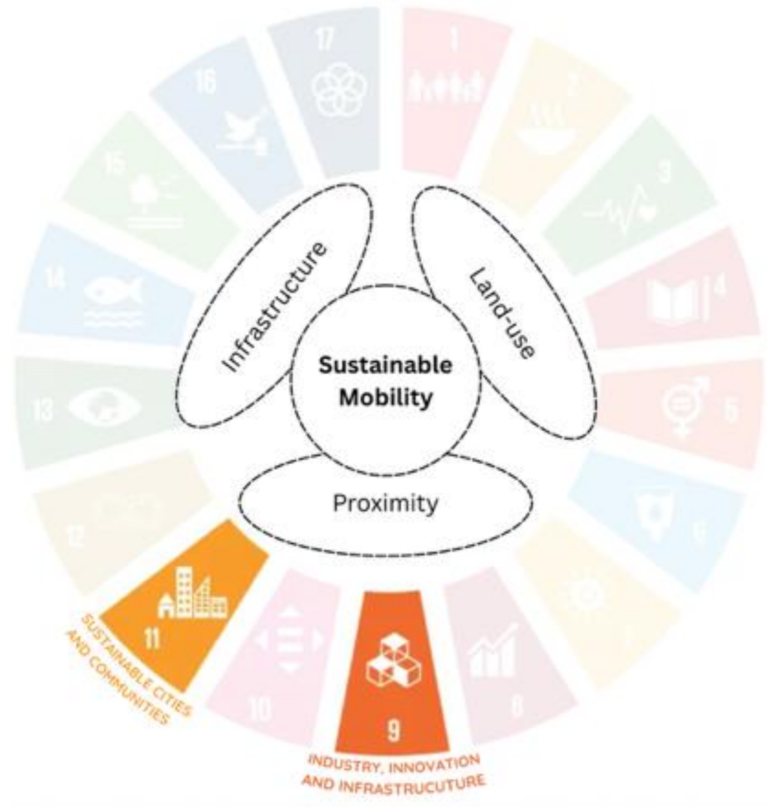
Guided by these methods, the study addresses the following research question: How can adaptive, community-driven intersection prototypes, supported by VR, enhance social sustainability, cultural identity, and everyday livability in Al Ain? By situating intersection redesign within broader debates on sustainable mobility and urban heritage, the paper positions Al Ain as a case study of global relevance, offering lessons for cities grappling with the dual pressures of modernization and cultural preservation.

2. Conceptual framework and methodology

2.1 Conceptual Framework

Conceptual Framework. The conceptual framework guiding this study integrates social sustainability, human-centered design, and community-driven urban networks. These principles are operationalized through participatory methods that combine digital innovation with cultural and environmental sensitivity, ensuring that technical performance is balanced with inclusivity and cultural continuity. Figure 1 illustrates the conceptual framework of the study, focusing on three main aspects. First, it utilizes open spaces and repurposes old buildings. Second, it emphasizes adaptive design methodologies utilizing VR technology. Third, it aims to enhance the infrastructure through the integration of green spaces and cultural equity.

Figure 1: Research conceptual framework (Authors, 2025)



2.2 Methodology

The research employed a mixed-methods qualitative approach that combined field observations, a community survey, and Virtual Reality (VR) scenario testing. Fieldwork was conducted at selected intersections in Al Ain, which are currently being transformed from roundabouts to signalized nodes. Direct observation focused on the physical, environmental, and social conditions of these sites, including the configuration of pedestrian pathways, the presence of shading and seating, microclimatic comfort, and how people used the spaces. Photographic documentation and field notes revealed challenges such as unsafe pedestrian crossings, limited greenery, and insufficient public amenities, but also highlighted opportunities for integrating mobility with socially inclusive design features.

To complement the observations, a structured community survey was distributed through municipal channels and field outreach, yielding fifty-five valid responses. The majority of respondents were young (54% aged 18–24 and 30% aged 25–34) and female (72%).

The final stage of the methodology employed Virtual Reality as both a design and participatory engagement tool. Three intersection prototypes—on-ground, elevated, and underground—were developed to explore alternatives for improving mobility while preserving cultural and environmental qualities. The model was created on Revit 2025 and Inscape, for the VR HTC Vive glasses used to test the scenarios.

In the next phase, two sets of VR workshops will be held: the first with municipal planners and engineers to assess technical feasibility, and the second with residents to evaluate the scenarios from the perspective of everyday experience. The immersive VR environment incorporated key community priorities identified through the survey and field observations, including shaded routes, safe crossings, public seating, and culturally sensitive design motifs. This will enable participants to interact with and critique the scenarios, offering feedback not only on traffic flow but also on broader social sustainability outcomes, including inclusivity, comfort, and cultural identity. By combining direct observation of existing conditions, quantitative insights from the community survey, and participatory testing through VR, the methodology established an iterative process that linked technical feasibility with social and cultural aspirations. This triangulation ensured that the proposed intersection prototypes were not only responsive to mobility demands but also contributed to community well-being and the preservation of Al Ain's urban identity.

VR is employed as both a design and engagement tool. Two sets of workshops are conducted: the first with planners and engineers from Al Ain Municipality, who provide insights on policy and technical priorities; and the second with residents, who evaluate intersection alternatives in relation to their everyday experiences. In both sessions, participants first explore the current intersection through VR before engaging with three proposed prototypes—on-ground, elevated, and underground. Their reflections inform iterative refinements to the designs.

Complementary to the VR workshops, surveys are distributed to residents and drivers in the surrounding neighborhoods. These surveys capture perceptions of pedestrian safety, traffic flow, accessibility, and the quality of public space, while also gathering input on desired improvements. The integration of municipal perspectives with everyday user experiences ensures that the final prototype addresses both policy frameworks and community aspirations.

A complementary goal is to enhance green infrastructure. Complying with sustainable design principles, the scenarios incorporate shaded pedestrian routes, green infrastructure, and socially active public spaces, which contribute to improved microclimatic conditions, enhanced walkability, and increased community interaction. Cultural identity is reinforced through the integration of heritage motifs and traditional urban patterns in street furniture and architectural elements. By embedding cultural continuity within modern design, the methodology ensures that intersection prototypes serve not only mobility functions but also broader social and cultural needs.

Ultimately, the three intersection scenarios are refined in compliance with Al Ain's planning codes. Based on feedback from both the municipality and community participants, one prototype is selected for detailed development and retested using VR. This iterative process demonstrates how adaptive, participatory, and culturally grounded planning can produce mobility solutions that extend beyond technical efficiency, strengthening equity, livability, and sustainable urban identity.

3. Results and Conclusion

3.1 Analysis of the Neighborhood

As demonstrated in Figure 3b, Al Mu'rated is considered a typical neighborhood in Al Ain, with low-rise residential buildings with commercial spaces on the ground floor for buildings facing the main road. In terms of walkability, the area contains walking infrastructure consisting of a pathway on the periphery, similar to the surrounding neighborhoods. The issues fall under several factors. First, the inconsistency of the paths, as they are present on parts of the neighborhood's edge while being absent from other parts, results in disconnected paths. Second, the lack of connectivity with the pathways from surrounding neighborhoods, all separated by car-dominant wide roads. Third, the location being on the edge of main roads lowers pedestrians' perceived safety, while insufficient canopy cover and limited social activities reduce comfort and place vitality. On the other hand, the interior of the neighborhood lacks any formal pedestrian paths.

Site visits had been conducted to visualize the behavior patterns of the residents closely. As shown in Figure 3b, residents utilize specific informal paths for walking. People's choice demonstrates the detachment of existing infrastructure and the natural behavior of residents.

Figure 3a: Key map of Al Mu'tared neighborhood (Authors, 2025)

Figure 3b: Analysis of connectivity and walkability in Al Mu'tared neighborhood (Authors, 2025)

Figure 3c: Land use in Al Mu'tared neighborhood (Authors, 2025)

3.2 Survey Results

The survey responses, which are 55 in total, highlight that most respondents are young (18–24), female, and students, living mainly in shared or family housing. Residents highlighted the lack of parks, sports facilities, and adequate lighting, emphasizing the importance of shaded walkways and inviting outdoor spaces. A majority are open to reusing old buildings if they are adapted, favoring community spaces, cafés/restaurants, and small workshops. Desired additions include community gardens, shaded seating areas, and quiet relaxation spaces. Regarding tourism, cultural and eco-tourism were considered the most appropriate options, with some interest in culinary tourism. Overall, the findings emphasize the community's desire for green spaces, safe and shaded walkability, and preservation of cultural identity, which would also support sustainable tourism.

The study's results combine insights from the community survey and VR scenario workshops, revealing consistent themes centered on walkability, adaptive reuse, and social sustainability. Survey findings show that the majority of respondents were young (54% aged 18–24 and 30% aged 25–34), with women making up nearly three-quarters of participants (72%). This demographic profile reflects the perspectives of a socially active and urban-oriented segment of the community. When asked about adaptive reuse of older structures, 54% indicated "maybe," 19% "yes," and 26% "no," reflecting cautious but generally positive attitudes toward integrating heritage buildings into contemporary urban life. The most preferred functions for such buildings were community gathering spaces (33 responses), cafés and restaurants (29), and small businesses or workshops (25), followed by museums and cultural centers (13) and tourist guesthouses (11).

Survey results underscored cautious but positive openness toward adaptive reuse of older structures, with 54% answering "maybe," 19% "yes," and 26% "no." Participants prioritized community gathering spaces, cafés and restaurants, small businesses, museums, and guesthouses as preferred services for reused buildings. They also identified the need for shaded walkways, public seating, safer pedestrian crossings, better lighting, and vehicle-free sidewalks as top public realm improvements. Notably, 80% of respondents agreed that adaptive reuse and intersection redesign could benefit the community, particularly through cultural, eco-, and community-based tourism. These findings provided grounded evidence of residents' aspirations and directly informed the design interventions tested through VR.

Responses regarding the public realm emphasized the community's priorities for safe, comfortable, and inclusive mobility environments. Shaded walkways were the most frequently cited need (42 responses), followed by public seating (33), safer pedestrian crossings (29), improved street lighting (24), and vehicle-free sidewalks (18). These priorities confirm that residents consider pedestrian comfort and safety to be central to sustainable mobility. Regarding tourism, 80% of respondents agreed that the adaptive reuse of Sha'abiat and redesigned intersections would benefit the community, particularly through cultural, eco-tourism, and community-based tourism. Collectively, the survey highlights the desire for spaces that not only improve mobility but also foster social interaction, community identity, and cultural continuity.

3.3 VR Workshops: Testing Intersection Prototypes through Immersive Participation

The VR scenarios further tested these outcomes by allowing participants to experience and evaluate three intersection prototypes: on-ground, elevated, and underground. Municipal planners emphasized the technical feasibility of the on-ground and elevated scenarios, noting their potential to balance traffic efficiency with public space integration. Residents, however, highlighted the social qualities embedded in the designs, particularly in scenarios that incorporated shaded pedestrian routes, seating areas, and green infrastructure. Feedback indicated that the on-ground scenario was perceived as the most relatable to everyday life, as it provided safe crossings and accessible community spaces without detaching pedestrians from the street environment. The elevated scenario was viewed as offering safety but at the risk of reducing social interaction, while the underground prototype was least favored due to perceptions of discomfort and disconnection.

Across both survey and VR results, a common thread emerged: communities in Al Ain value intersection designs that integrate walkability, shading, and cultural motifs with mobility infrastructure. The ability to visualize and interact with the designs in VR enhanced residents' capacity to articulate their preferences, bridging technical proposals with lived experience. These results underscore that intersection redesign can serve as more than a mobility intervention; when approached through participatory and culturally sensitive processes, it becomes a catalyst for social sustainability, community interaction, and the preservation of Al Ain's urban identity.

The next stage of the study will involve testing the proposed VR scenarios with both municipal experts and community participants. Three prototypes—on-ground, elevated, and underground—have been developed to examine different approaches to balancing mobility efficiency with the integration of public space. Initial expert review suggests that the on-ground and elevated options may offer the strongest technical feasibility, particularly in terms of traffic flow and regulatory alignment. However, their broader social qualities remain to be evaluated by residents, who will experience the scenarios through immersive VR sessions. The testing will focus on how features such as shaded pedestrian routes, seating areas, and green infrastructure influence perceptions of safety, comfort, and inclusivity. It is anticipated that the on-ground scenario will resonate most with everyday community needs, while the elevated and underground alternatives may raise questions about social interaction and accessibility.

The VR scenarios demonstrated that intersection redesign can move beyond technical efficiency to deliver socially sustainable outcomes. As shown in Figure 2, integrating shade, greenery, and community seating transformed the intersection into a civic space that supports walkability, cultural identity, and everyday livability. These findings underscore the importance of embedding social and cultural values into mobility infrastructure, ensuring that Al Ain's urban transformation enhances both connectivity and community well-being.

Figure 2: Shots taken using the VR demo generated from the research data by Nicolas Monje Mejia, 2025

4. Conclusion

By extending the process into participatory VR testing, the project validates survey findings that highlighted the importance of walkability, shading, and cultural continuity in intersection design. The upcoming workshops provide residents with a tangible, interactive platform to articulate their preferences, ensuring that technical proposals are grounded in their lived experiences and cultural values. Ultimately, the study demonstrates that intersection redesign in Al Ain is not only a question of traffic management or technical feasibility. When combined with participatory VR workshops, these interventions become an opportunity to weave mobility planning with cultural identity, community interaction, and long-term urban sustainability.

The study concludes that VR workshops are more than a research tool—they are a bridge between professional planning expertise and community knowledge. By placing residents at the center of design evaluation, VR facilitates a richer, more inclusive dialogue on the future of urban infrastructure. In doing so, it strengthens the role of planning not just as a mobility intervention, but as a catalyst for preserving Al Ain's unique urban identity while preparing the city for future mobility demands.

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Ethical Considerations

The study obtained ethical approval from the UAE University (UAEU) Research Ethics Review Board (Ethical Application No. ERSC_2023_2673).

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CHAPTER 2

MASS CUSTOMIZATION: TECHNOLOGY AND PRACTICES

SYSTEMIC REFORM FOR VICTORIA'S HOMELESSNESS CRISIS THROUGH ARTIFICIAL INTELLIGENCE, MODULAR CONSTRUCTION AND INTERNATIONAL ALLIANCES

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ABSTRACT

Victoria's homelessness crisis, intensified by systemic shortcomings in construction processes and housing affordability, demands urgent and innovative solutions. This study proposes a comprehensive systemic reform workflow that integrates mass customisation technologies, artificial intelligence (AI)-driven design, and advanced construction techniques. It leverages Japan's in-factory robotics for efficient modular construction and establishes global supply chain partnerships, including China's cost-effective, expandable, and foldable prefabricated compact pod homes. The research aims to address Australia's homelessness crisis by delivering scalable, low-carbon housing solutions tailored to urban contexts like Victoria. Through detailed analysis of data and case studies, the study identifies key barriers in traditional construction, including prohibitively high costs, extended project timelines, and inconsistent quality. It proposes reforms that utilise artificial intelligence to streamline architectural design and expedite council approval processes, while Japan's robotic in-factory systems enable rapid, high-precision module production to significantly reduce construction timelines. China's prefabricated pods provide a practical solution for permanent emergency housing, offering affordability and adaptability.

These integrated solutions align with the Zero Energy Mass Customisation Housing (ZEMCH) mission to deliver equitable, sustainable, and scalable housing through advanced technologies and optimised global supply chains. The proposed framework has potential applications beyond Australia, addressing global housing challenges in regions facing similar urbanisation and affordability issues.

Keywords: Mass customisation; Modular construction; Artificial intelligence; Prefabricated housing; Supply chain management; Homelessness; Sustainable housing.

1. Introduction

Homelessness in Victoria Australia has reached critical levels with approximately 10,000 individuals becoming homeless each month exacerbated by a 29% surge in rental inflation over the past four years (The Guardian 2024; News.com.au 2024). Systemic inefficiencies in the construction sector characterised by soaring costs prolonged project timelines and suboptimal quality severely limit the delivery of affordable housing. These challenges are compounded by regulatory bottlenecks and a lack of scalable sustainable construction methods. This paper addresses the ZEMCH 2025 conference themes of mass customisation technologies and practices as well as modular construction and supply chain management to propose a transformative approach to Victoria's housing crisis.

In 2023–24, ≈280,100 clients were assisted by specialist homelessness services nationally, including ≈102,000 clients in Victoria, the highest of any state. The rate of assistance equated to 105.1 clients per 10,000 population (AIHW 2024).

The central research question is: How can AI driven mass customisation and global modular construction partnerships effectively address homelessness in Australia? This study introduces a systemic reform workflow that integrates cutting edge technologies and international collaboration. Specifically, it combines AI driven design optimisation Japan's advanced in factory robotics for modular construction and China's innovative prefabricated compact expandable or flatpack homes which are both cost effective and adaptable (expandable and foldable). This approach not only aims to deliver affordable low carbon housing at scale but also ensures rapid deployment to meet urgent needs. By leveraging global supply chains and advanced technologies the proposed framework offers a scalable model with relevance to global housing challenges. This approach delivers rapid, affordable, low-carbon housing, with potential applications in urbanising regions, in regions where housing is self-built and informal settlements are prevalent (Monkkonen, 2018). The significance of this research lies in its holistic integration of technology policy reform and international cooperation to create equitable and sustainable housing solutions.

Drawing on a systemic approach, this study frames the homelessness crisis as a complex system requiring integrated solutions. Systems thinking emphasises holistic interactions between components, enabling the coordination of AI, robotics, and global supply chains to address cost, time, and quality barriers. Mass customisation, defined as flexible manufacturing of tailored housing units at scale, supports diverse and somewhat customisable housing needs whether that be through compact homes or modular construction.

AI driven design leverages algorithms to optimise cost and energy efficiency (Peixoto et al. 2021), while advanced construction technologies, such as robotic automation and/or prefabrication, enhance production efficiency. This theoretical foundation underpins a cohesive workflow that delivers equitable, sustainable housing, with potential applications in global urban contexts facing similar challenges.

2. Methodology

This study employs a systematic analysis to investigate construction related barriers to affordable housing in Victoria utilising post 2020 data from reputable sources such as the Australian Institute of Health and Welfare (AIHW 2024) and Deloitte (2025). The research design incorporates case studies of advanced construction practices including Japan's in factory robotics systems (Curbed 2017;

Japan Prefabricated Construction Market 2025) and Chinas prefabricated compact pod homes (DeepBlue SmartHouse 2021).

2.1 Data Collection

Quantitative data on homelessness trends, construction costs, and public service expenses are sourced from government reports (AIHW 2024) and industry analyses (Deloitte 2025). Qualitative insights are drawn from case studies of Japan’s robotic modular construction (Curbed 2017; Japan Prefabricated Construction Market 2025), China’s prefabricated pod homes (DeepBlue SmartHouse 2021), and global social housing initiatives (Monkkonen 2018).

2.2 Development of the Conceptual Framework

The conceptual framework was developed through a systematic literature review and case study synthesis. Literature on AI driven design (Peixoto et al. 2021), robotic construction, and global supply chains informed the integration of technologies into a cohesive workflow. Case studies of Japan’s Sekisui Heim and China’s DeepBlue SmartHouse provided practical insights into scalable, cost-effective solutions. The framework combines AI for design optimisation, robotic in factory production for modular units, compact prefabricated pods and global supply chains for efficient delivery, addressing systemic barriers like high costs and regulatory delays. This process ensures a replicable model tailored to Victoria’s urban context and applicable globally.

2.3 Analysis

A cost benefit analysis evaluates financial viability, estimating investment costs against savings from reduced public service reliance. Thematic analysis of case studies identifies key barriers and solutions, while comparative analysis assesses the framework’s applicability to Victoria, focusing on urbanisation rates and construction inefficiencies.

This methodology addresses a knowledge gap in combining AI, robotics, and global partnerships, offering a replicable model for urban housing challenges.

2.4 Conceptual Framework

The proposed systemic reform workflow integrates three technological pillars within a systems thinking approach:

1. **AI Driven Design Optimisation**
    - Algorithms streamline architectural design for cost, energy efficiency, and durability.
    - Automated compliance checks accelerate council approvals.
    - Predictive analytics support proactive maintenance and lifecycle planning.
2. **Robotic Modular Construction (Japan)**
    - Automated factory systems enable rapid, high precision production of modules.
    - Capacity to manufacture up to 150 housing units daily, reducing timelines by around 25 per cent.

    - Supports mass customisation to meet diverse housing needs.

3. **Compact and Expandable/Flatpack Pod Homes**
    - Prefabricated compact pods from China provide cost effective, expandable and foldable units for emergency and permanent housing.
    - Available as flatpack or expandable in 1-, 2- or 3-bedroom configurations.
    - Supports mass customisation to meet diverse housing needs.
4. **Global Supply Chain Integration (China and Japan)**
    - Strategic partnerships ensure stable supply chains, reducing material shortages and local bottlenecks.
    - Just in time delivery minimises delays and inefficiencies.

Workflow Integration:

These pillars are sequenced into a systemic process: AI first optimises designs, Japan's robotics accelerates modular production, and/or Chinese prefabricated pods support scalable delivery. The integrated workflow produces affordable, low carbon housing at speed and scale, addressing systemic barriers such as high costs, regulatory delays, and supply chain inefficiencies.

This conceptual framework underpins the subsequent analysis and results, providing a structured model for reforming Victoria's housing system while offering global applicability.

3. Results and Discussion

3.1 Systemic Barriers

Victoria's construction sector faces significant challenges that hinder affordable housing delivery. Despite significant investment, 37,800 clients experienced persistent homelessness in 2023–24. Family and domestic violence remains a leading driver, cited as the main reason for assistance by 26% (≈71,800 clients). Moreover, about 31% of clients who needed short-term, or emergency accommodation did not receive it. (AIHW 2024)

Victoria's construction sector faces significant obstacles:

- **High Government Expenditure**: The Federal Government spends over $200 billion on welfare payments each year. (Deloitte 2025).
- **High Construction Costs**: Following the initial shock of the COVID-19 pandemic, prices received by building construction businesses have increased 31.1% from September quarter 2020 to June quarter 2024, driven by growth in house construction prices which rose 40.8% over this period. (ABS 2024).
- **Regulatory Delays**: Council approvals extend timelines by up to 12 months.
- **Supply Chain Issues**: Material shortages and logistical inefficiencies delay projects by approximately 20–30%.

- **Quality Concerns**: Substandard materials contribute to health issues like mould, increasing maintenance costs.

In other countries, similar barriers exist, with high housing prices, high government expenditure and limited credit access forcing households into self-built or informal built housing, often in peripheral areas with poor infrastructure.

3.2 Mass Customisation: Technology and Practices

Mass customisation technologies offer innovative solutions to overcome these barriers:

- **Japan's In Factory Robotics**: Companies like Sekisui Heim utilise automated production lines to manufacture up to 150 modular housing units daily reducing construction timelines by approximately 25% (Curbed 2017). This approach supports customised designs tailored to diverse needs such as emergency shelters for individuals or larger units for families.
- **AI Driven Design**: AI algorithms optimise architectural plans for cost efficiency structural durability and energy performance reducing material waste by up to 15%. AI also streamlines council approval processes by automating compliance checks cutting approval times by an estimated 30%.
- **Predictive Maintenance**: AI powered Internet of Things (IoT) sensors monitor building conditions in real time detecting issues like mould or structural weaknesses early thereby enhancing long term quality and reducing maintenance costs (London IoT Housing Trial 2023).

These technologies enable the production of high-quality customised housing at scale aligning with ZEMCHs focus on innovative sustainable construction practices.

3.3 Modular Construction and Supply Chain Management

Modular construction supported by optimised global supply chains enhances the efficiency and scalability of housing delivery:

- **AI Driven Design**: AI algorithms optimise architectural plans for cost efficiency, structural durability, and energy performance, reducing material waste by 15%. Automated compliance checks streamline council approvals, cutting timelines by 30%.
- **China's Prefabricated Pods**: Companies like DeepBlue SmartHouse produce cost effective rapidly assembled pod homes that are expandable and foldable making them ideal for permanent emergency housing in crises such as family violence or sudden homelessness (DeepBlue SmartHouse 2021). These pods can be deployed within hours compared to months or even years for traditional construction.
- **Japan's Robotic Modular Construction**: Japan's Sekisui Heim uses automated production lines to manufacture 150 modular units daily, reducing construction timelines by 25% (Curbed 2017). This supports tailored designs for diverse needs, from emergency shelters to family units.

- **Global Partnerships**: Strategic collaborations with Japanese and Chinese manufacturers ensure a steady supply of modular components mitigating local material shortages and logistical bottlenecks. These partnerships facilitate just in time delivery reducing project delays. These partnerships support may face challenges in comparison to informal construction practices.

These solutions integrate with mass customisation by using AI and robotics to produce tailored modules which are then efficiently delivered via global supply chains.

3.4 Integration and Impact

The workflow integrates AI, robotics, and global supply chains to deliver tailored, high-quality housing rapidly. Globally, AI-driven site selection and prefabricated pods could address informal settlements, with potential energy savings of 50% in tropical climates using passive design (Saldaña-Márquez, 2018).

3.5 Global Applicability

The framework is highly applicable globally, where rapid urbanisation and a housing deficit mirror Victoria's challenge. AI-driven design can optimise site selection, while China's prefabricated compact homes (pods) could address informal settlements. Japan's robotics could enhance the modular construction industry in both urban and rural areas, reducing costs and timelines in other countries.

4. Conclusion and Future Work

This study presents a systemic reform workflow integrating AI-driven mass customisation, Japan's robotic modular construction, and China's prefabricated pods to address Victoria's homelessness crisis. The approach reduces costs and timelines whilst ensuring sustainable, high-quality housing. By leveraging AI to optimise design and streamline approvals, Japan's robotic systems to accelerate modular production, and/or China's cost-effective prefabricated compact pods for rapid deployment, the framework tackles systemic barriers such as high construction costs, regulatory delays, and supply chain inefficiencies. These solutions align with the Zero Energy Mass Customisation Housing (ZEMCH) mission to deliver equitable, low carbon housing, offering a scalable model for urban contexts like Victoria. The significance of this research lies not only in its potential to mitigate Victoria's homelessness crisis but also in its adaptability to global urban challenges, particularly in regions with rapid urbanisation and informal housing settlements. The integration of advanced technologies and international partnerships establishes a replicable blueprint for delivering affordable, sustainable housing at scale, addressing a critical global need for equitable urban development.

Limitations include high initial investments for AI and robotic systems, which may pose financial challenges for widespread adoption, and policy and regulatory barriers that could hinder the integration of advanced technologies into existing regulatory frameworks. Additionally, the reliance on global supply chains introduces risks related to geopolitical uncertainties and logistical complexities, which could affect project timelines and costs. Cultural and contextual differences in housing needs across regions may also require tailored adaptations of the proposed framework, particularly in informal settlements where community engagement and local materials play a significant role (Monkkonen, 2018).

Future research should explore real time AI supply chain optimisation to further reduce logistical delays and enhance cost efficiencies, particularly in dynamic global markets. Scalability studies in regions with prevalent informal housing and energy inefficiencies, such as parts of Southeast Asia, Africa, and Latin America, could validate the framework's global applicability.

Practical applications include pilot projects in Victoria to test the integration of AI-driven design and prefabricated pods in real world urban settings, potentially in collaboration with local councils and international manufacturers.

Further investigation into community driven customisation processes could ensure that housing solutions meet diverse social and cultural needs, enhancing occupant satisfaction and long-term sustainability. Partnerships with governmental and non-governmental organisations and global housing initiatives could also facilitate knowledge transfer and funding for implementation. This work advances ZEMCH's mission of equitable, low carbon housing through innovative technology and global collaboration, paving the way for transformative housing solutions worldwide.

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FROM WASTE TO SHELTER: SOCIAL AND ENVIRONMENTAL IMPACT OF USING RECYCLED PET IN SUSTAINABLE HOUSING

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ABSTRACT

Two intertwining issues that impact cities globally, especially in emerging nations, are plastic pollution and the housing shortage. With an emphasis on the case of Arequipa, Peru, this article investigates the possibilities of recycled polyethylene terephthalate (PET) as a sustainable building material for social housing. It describes the amount of plastic garbage and its effects on the environment, based on both local and global data, and shows how poorly managed waste is linked to circumstances of informal living in the city's peri-urban areas. The paper examines the technical benefits of PET bricks, such as their durability, cost, and thermal performance, and places them in the context of larger discussions about the circular economy and sustainable building practices. It also takes into account strategies to integrate policies through community-based projects, incentives, and regulatory standards. PET bricks address garbage and housing at the same time, in contrast to traditional methods that do it separately. The article concludes by highlighting the social ramifications of PET-based housing solutions, namely how they may enhance vulnerable groups' comfort, health, energy efficiency, and employment prospects. The results imply that turning waste into shelter is a step toward social justice and resilient urban development in addition to being an environmental tactic.

Keywords: Recycled PET; sustainable housing; informal settlements; waste management; Arequipa ; circular economy; thermal comfort

1. Introduction

One of the most pressing environmental issues of the twenty-first century is plastic pollution. Over 390 million tons of plastics are produced annually worldwide, up from 2 million tons in 1950. A large amount of this waste is mishandled and eventually finds its way into both terrestrial and marine ecosystems (Geyer, Jambeck, & Law, 2017). Because of microplastics and related hazardous compounds, such mismanagement endangers biodiversity, disturbs ecological processes, and endangers human health (Rochman, Browne, & Halpern, 2013). Polyethylene terephthalate (PET), which is mostly utilized in bottles and packaging, is one of the most often consumed polymers. PET alone accounts for a major share of plastic trash, although recycling systems remain inadequate in most countries, leaving enormous volumes uncontrolled and compounding environmental dangers (World Economic Forum, 2015).

At the same time, the shortage of affordable housing remains a critical global issue, particularly in rapidly urbanizing regions. According to UN-Habitat (2020), over 1.6 billion people worldwide lack access to adequate housing. The convergence of these crises—plastic pollution and housing deficits—presents opportunities for integrated solutions. One promising approach is the transformation of PET waste into construction materials, such as bricks and blocks for social housing. Research has demonstrated that PET-based composites can achieve sufficient mechanical strength, thermal insulation, and durability for use in low-cost housing, thereby reducing both plastic pollution and the housing deficit (Hassan, et al., 2022).

An interesting setting for analyzing this junction is Arequipa, Peru. In recent decades, the city has seen substantial urban growth, and informal settlements have spread throughout its peri-urban areas (Zeballos, 2024). Poor building materials frequently jeopardize thermal comfort, structural safety, and resistance to natural disasters like floods and earthquakes in these communities (Calderón Cockburn, 2017). PET-based bricks are an inventive and regionally relevant substitute in this regard. These materials enhance waste management and facilitate the development of decent, reasonably priced housing by repurposing plastic waste into a building material.

This essay explores the local and worldwide dynamics of plastic pollution, the unique problems with Arequipa's informal housing and waste management, and the possibility of integrating PET bricks into social housing regulations. In keeping with the Sustainable Development Goals (SDGs) of the UN, particularly SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production), it also emphasizes the social and environmental advantages of implementing this technology, especially for marginalized communities.

2. Global and Local Figures on Plastic Pollution

It is astounding how big the plastic catastrophe is. Nearly half of the 400 million tons of plastic produced worldwide each year are intended for single-use applications, according to the United Nations Environment Programme. Over thirty percent of trash from plastic packaging comes from PET bottles alone. Only over 9% of plastics are recycled worldwide; the remaining 79% end up in landfills or the environment. Usually, the leftover portion is burned, creating toxic pollutants that exacerbate climate change. Also, nearly 17,000 tons of plastic waste are produced and dumped in open landfills every day throughout the Caribbean and Latin America, with negative effects on the environment, the economy, aquatic life, the aesthetics of seashores, and public health. The ecosystem and public health are under risk due to the growing usage of plastics (Husaini et al., 2024).

Latin America has significantly lower recycling rates, with an average of less than 15%. This is mostly because there is little investment in recycling infrastructure, inadequate collection systems, and lax regulatory frameworks. This trend is evident in nations like Peru, where a sizable amount of plastic garbage gets disposed of inappropriately. The buildup of plastic leftovers in urban areas like Arequipa puts further strain on waste management systems that are already under stress and increases environmental hazards in informal settlements and peri-urban areas.

According to local data from the Environmental Atlas of Arequipa (2024), the region's garbage generation has been gradually rising and has recently surpassed 900 tons per day. Non-biodegradable materials make up a sizable portion of this, with PET being one of the most noticeable substances found in landfills, waterways, and empty lots. When taken as a whole, these numbers highlight how urgent it is to move away from disposal and toward resource recovery, which turns garbage into useful commodities that may solve social and environmental issues.

3. Waste Problems in Arequipa and Their Relationship with Informal Housing

More than a million people live in Arequipa, the second-largest city in Peru and a fast growing metropolis (INEI, 2017). Natural and socioeconomic factors, such as its volcanic terrain, arid desert climate, and seismic vulnerability, as well as migration-driven demographic pressure, social inequality, and a shortage of formal housing supply, have all influenced its urban growth (Bebbington & Williams, 2008). Due to these factors, informal communities have grown throughout the metropolitan area, especially in high-risk areas like riverbanks, volcanic slopes, and the outskirts of desert regions (Zeballos, et al., 2021).

Many of these villages lack suitable building materials, stable land ownership, and basic infrastructure, according to the Atlas Ambiental de Arequipa. Families frequently use salvaged materials, unfinished concrete blocks, or adobe to build things themselves. Although these methods save money in the short term, they jeopardize long-term durability, seismic resistance, and thermal comfort—all of which are crucial in a metropolis that experiences large daily temperature fluctuations and seismic susceptibility (Zeballos, 2024) .These vulnerabilities are strengthened by ineffective houing policies, which prolong cycles of social exclusion, poverty, and environmental degradation .

Mismanagement of waste exacerbates these issues. Open dumping and burning of plastics are commonplace in Arequipa's peri-urban areas, exposing residents to tainted soil, water, and air (IMPLA, 2016). Because the available land in these regions is uncontrolled and economically accessible, informal communities usually inhabit or border these trash collection sites. This leads to two crises: tens of thousands of families are compelled to live in unstable and dangerous housing circumstances, while massive amounts of PET and other plastics are left unmanaged.

In this regard, incorporating recycling into house plans provides a creative and pertinent local solution. It has been demonstrated that turning PET waste into building materials, like bricks, panels, or insulation components, can reduce environmental impacts while also giving low-income households access to resilient and reasonably priced building options (Abouhadid et al., 2019). By tying waste reduction to better housing for vulnerable populations, this dual-benefit strategy supports global sustainability goals, especially the Sustainable Development Goals (SDGs 11 and 12) (United Nations, 2015). Arequipa is a prime location for the investigation and implementation of such integrated solutions because of the city's combined challenges of informal urbanization and poor waste management.

4. PET Bricks and Their Integration into Social Housing Policies

In recent years, recycled PET bricks have become more well-known as a creative and environmentally friendly substitute for traditional materials. Despite being lighter than concrete or clay blocks, these bricks—which are made by shredding PET bottles and mixing them with binders or additives—offer substantial thermal and acoustic insulation. They can be used in a variety of settings because to their resilience to moisture and pests, especially in areas that are vulnerable to earthquakes and severe weather.

The economic and environmental benefits of employing recycled polyethylene terephthalate (PET) in building, especially in social housing, have drawn attention. Its feasibility in this industry has been shown by a number of projects (UNDP, n.d.; Conceptos Plásticos, 2024; Kenoteq, n.d.; Bloqueplás, 2017). In a similar vein, Angumba Aguilar (2016) assessed bricks with 25% PET for non-load-bearing masonry and discovered that they offer superior thermal insulation over more conventional materials like clay and adobe brick, which lowers energy consumption and enhances home comfort.

Integrating PET bricks into social housing policies could therefore generate multiple benefits:

- Environmental: reducing plastic waste, promoting circular economy practices, and lowering greenhouse gas emissions.
- Economic: lowering construction costs through lighter materials, reduced transport expenses, and decreased household energy bills due to better insulation.
- Social: providing more comfortable and resilient housing for vulnerable families, thus improving health, well-being, and quality of life.

To realize these benefits, several policy instruments could be employed:

1. Establishing regulatory standards to certify the safety and performance of recycled PET bricks.
2. Introducing tax breaks or subsidies to incentivize companies producing recycled construction materials.
3. Incorporating PET bricks into public housing pilot projects to demonstrate feasibility and scalability.
4. Developing community-based recycling systems that engage residents in PET collection and transformation, while creating local employment opportunities.

Global agendas like the Sustainable Development Goals (SDGs) of the UN, especially Goals 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production), would be in line with such tactics. Governments can promote social justice, economic efficiency, and environmental sustainability all at once by incorporating PET bricks into legislative frameworks.

Increased techno-economic viability for large-scale recycled-plastic masonry systems is demonstrated by recent real-world implementations. Bloqueplás, a commercially available interlocking PET block technique that enables quick assembly with less mortar, was created by Grupo Ecoplasso in Colombia. This system has been deployed in several Latin American nations, exhibiting market adoption beyond pilot stages and the possibility for reproducible production, with a listed unit price of roughly US$4.60 per block (Engineering for Change, 2021).

UNICEF and Conceptos Plásticos collaborated to create a similar project in West Africa, setting up a specialized recycling facility in Côte d'Ivoire to turn local plastic trash into modular bricks for classroom building. According to UNICEF project reports, the facility processes more than 9,000 tonnes of plastic per year, which allows for the building of more than 600 classrooms at an average cost of about US$14,500 per school (UNICEF, 2019). Despite being context-dependent, these numbers show repeatable implementation, transparent project-level costing, and well-organized supplier chains—all of which are essential markers of scalability in circular construction (Bovea et al., 2010).

In addition to Latin America and West Africa, the Kenyan social company Gjenge Makers has shown success in scaling up the use of recycled plastic in building. At around KES 850/m^2 (US$7.7), their plastic paving bricks—which are made from polyethylene waste—offer competitive unit economics for long-lasting and reasonably priced uses in public infrastructure. The company's creative upcycling of post-consumer plastics has received international recognition for its role in reducing environmental waste and creating jobs (Waita, 2021).

All of these instances point to the transition of recycled-plastic masonry technologies from pilot projects to commercially feasible models. Localized manufacturing, predictable cost structures, modularity, and a decreased reliance on traditional materials are some of its key scaling characteristics (Al-Salem, et al., 2009). To assess their long-term viability in social housing schemes, further peer-reviewed, context-specific Life Cycle Cost (LCC) and Techno-Economic Assessment (TEA) studies are required. To guarantee compatibility with both environmental and socioeconomic development goals, such studies should take into account factors including material movement, labor dynamics, certification procedures, and maintenance regimes.

5. Potential Impact on Vulnerable Communities

Especially for vulnerable populations in informal settlements, the social dimension of incorporating polyethylene terephthalate (PET) bricks into housing schemes is crucial. These groups frequently face unstable housing circumstances that include high energy costs, health risks, thermal discomfort, and a lack of resilience to environmental dangers. For instance, in Arequipa, winter nighttime lows frequently drop below 10 °C, and the city experiences strong solar radiation during the day, resulting in abrupt thermal fluctuations that worsen energy poverty and health risks (Zeballos, 2024). Due to their low thermal insulation, traditional self-built materials like adobe and unpainted concrete blocks cause rooms to overheat during the day and become cold at night.

Bricks made from recycled PET provide a useful and affordable substitute. Recycled plastics can enhance thermal comfort and lessen the demand for artificial heating or cooling systems, according to studies (Abouhadid et al., 2019). This directly addresses the interconnected problems of energy poverty and public health by lowering energy costs and creating healthier indoor conditions for low-income households. Furthermore, proper housing improves social and psychological well-being in addition to providing physical shelter, bolstering security, dignity, and general quality of life (Evans, 2003). Better housing promotes community cohesion, improves learning circumstances for kids, and increases the ability to adapt to the effects of climate change.

There are also major socioeconomic advantages to the manufacture and use of PET bricks. By creating jobs in the collection, sorting, and manufacture of plastic trash, recycling-based enterprises can integrate traditionally excluded workers, known as informal recyclers, into more structured and secure value chains (Wilson et al., 2006). These prospects, which not only create new revenue streams but also promote social inclusion, are especially advantageous for women and young people (Walker, 2008).

From a policy standpoint, including PET bricks into social housing initiatives may spark a more extensive shift toward inclusive and sustainable urban design. Cities like Arequipa can establish themselves as regional leaders in the adoption of circular economy solutions in developing environments by clearly connecting social justice, housing quality, and waste management (Geissdoerfer et al., 2017). The Sustainable Development Goals, particularly SDG 11 on sustainable cities and SDG 12 on responsible consumption and production, would be in line with such activities.

6. Conclusion

Especially for vulnerable populations in informal settlements, the social dimension of incorporating polyethylene terephthalate (PET) bricks into housing schemes is crucial. These groups frequently face unstable housing circumstances that include high energy costs, health risks, thermal discomfort, and a lack of resilience to environmental dangers. For instance, in Arequipa, winter nighttime lows frequently drop below 10 °C, and the city experiences strong solar radiation during the day, resulting in abrupt thermal fluctuations that worsen energy poverty and health risks (Zeballos, 2024). Due to their low thermal insulation, traditional self-built materials like adobe and unpainted concrete blocks cause rooms to overheat during the day and become cold at night.

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DEVELOPING A PLANNING AND CONTROL MODEL FOR MODULAR CONSTRUCTION MANUFACTURING BASED ON THE LEAN PHILOSOPHY

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ABSTRACT

Modular Construction (MC) is a prefabricated system in growing demand in several countries. It has potential to increase productivity, quality, and safety, and to reduce lead times, being associated to the effort of making construction more sustainable. Despite its potential, production methods and management tools used in many MC manufacturing plants are often similar to those of conventional construction. This paper presents the preliminary results of a research study that devised a planning and control (P&C) model for MC factories, focused on module assembly and finishing, based on Lean Production concepts and principles, including the combination of two P&C methods: Last Planner System and Takt Production. Design Science Research was the methodological approach adopted in this investigation, developed in close collaboration with a MC company in nine months of fieldwork in its manufacturing plant. The research was divided into three phases: understanding the problem; co-developing, implementing, and refining the P&C model; and analyzing and reflecting on results. The model is hierarchically structured (long-, medium-, short-term), defines the decision scope of each level, and connects them to the management of the project supply-chain. Key concepts and principles include standardization, basic stability, location-based planning, leveling and synchronization of operations, and continuous improvement.

Keywords: Manufacturing plant; Customization; Last Planner System; Production Planning and Control; Lean Production.

1. Introduction

Off-site component manufacturing has been adopted worldwide as a strategy to improve performance in the construction industry (Altaf et al., 2018; Feldmann, 2022). In Modular Construction (MC), two- or three-dimensional modules are produced in a factory environment and then installed on-site (Gibb, 1999). It usually involves a high level of prefabrication among off-site systems, as most components (i.e., finishings) are executed in the controlled environment of a factory (Hussein et al., 2021). MC can potentially increase productivity, quality, and safety, and reduce lead time and waste, which contributes to make construction more sustainable (Pan & Hon, 2020). There is a growing adoption of MC in several countries, such as Japan, UK, Australia, Singapore, USA, China, Canada, Sweden, Brazil, and Malaysia (Pan & Hon, 2020).

Manufacturing plants play an important role in the complex MC supply chain, as most of the activities that add value to the product are performed in a controlled environment. However, due to the complex and unique nature of MC projects, many factories still operate with relatively low levels of automation and mechanization (Altaf et al., 2018; Feldmann, 2022; Ferreira, 2024; Hussein et al., 2021; Yu et al., 2013). Although modules are built in a factory environment, the production methods and management tools used in many factories are often similar to those of conventional construction, including traditional processes such as painting, drywall, and tiling (Feldmann, 2022; Ferreira, 2024; Yu et al., 2013).

The application of Lean Philosophy in MC remains underexplored (Hussein et al., 2021), although its core concepts and methods can potentially increase process stability and help manage the inherent complexity of construction projects (Hamerski et al., 2024; Innella et al., 2019; Koskela, 2000). Stability can be defined as the ability to produce predictable results over time, which enables the creation of a consistent workflow (Liker & Meier, 2007). By contrast, instability results from variability in processes (Liker & Meier, 2007). Two production planning and control (P&C) methods, derived from the Lean Production concepts and principles, can potentially be used in MC: the Last Planner System (LPS) (Ballard & Howell, 1998) and Takt Production (Tommelein et al., 2024).

LPS addresses construction typical uncertainty and variability through planning hierarchization, systematic identification and removal of constraints, collaborative planning across multiple instances, and contingency plans (Ballard & Howell, 1998; Hamerski et al., 2024). LPS proposes that only "workable" tasks are scheduled (shielding production mechanism), controlling work-in-progress (WIP), reducing variability, and enabling continuous flow (Ballard & Howell, 1998). This focus on predictability establishes the foundation of stability required before advancing to more sophisticated lean practices (Ballard, 2000).

Takt Production (TP) applies several concepts and principles of Lean Philosophy, such as batch size reduction, WIP control, standardized work, and process synchronization (Tommelein et al., 2024). Synchronization is particularly important for module assembly and finishing activities, as modules carry different workloads, a common challenge among MC factories (Hussein et al., 2021). TP prioritizes the synchronization of activities by dividing the project into zones and establishing a production rhythm (takt), which is achieved through a detailed structuring of work with similar cycle times, in a collaborative way (Tommelein, 2017).

This research work sought to answer the following question: "How can LPS and TP contribute to achieving stability and managing complexity in MC factories?" The main objective of this investigation is to develop a P&C model for MC factories, being focused on the stages of module assembly and execution of finishings. It considers the context of a MC company undergoing a transition from artisanal to industrialized processes by implementing Lean Production philosophy. These are the secondary objectives of this investigation: (i) analyze the role of LPS in stabilizing production in the MC factory environment; and (ii) analyze the complementarity of LPS and TP in P&C of MC projects. Thus, grounded in a practical application of Lean in a manufacturing plant, the research offers replicable solutions that can contribute to make MC more industrialized and sustainable.

2. Research Method

Design Science Research (DSR) was the methodological approach adopted in this investigation, as it enables the concept solution (named artefact) of a class of real-life problems while providing a prescriptive theoretical contribution (Holmström et al., 2009). As the first author of this paper worked actively in co-developing, implementing, analyzing, and refining the artifact, this study can be classified as Action Design Research (ADR) (Sein et al., 2011). The artefact devised in this investigation is a production P&C model for MC factories in the process of transitioning from traditional to industrialized construction technologies.

The research was conducted in three phases: (i) understanding the practical problem in the context of the MC company involved in this study; (ii) developing and implementing a production P&C model through an empirical study of module assembly and finishing; and (iii) analyzing and reflecting on the results. The study began in November 2022 and was completed in August 2023.

In the first phase, data were collected aiming to identify production problems and challenges, to understand the nature of module assembly and finishing activities, and to examine meeting and planning routines. In the second phase, a P&C model was proposed and implemented, building upon the findings from the first phase and the Lean Production philosophy literature. Inspired primarily by the LPS System, the model underwent refinement cycles, closely monitored by the researcher. Training sessions were also held with the company's team during these cycles. Beyond the P&C model itself, additional implementations, also based on Lean Philosophy concepts and principles, were introduced (some suggested by the researcher, others initiated by the company), including: supporting tools for production P&C and for communication with other supply-chain sectors, production-line layout changes, a training program, a replenishment island, and the development of equipments and materials kits. The third phase comprised analysis and reflection on the results, based on (i) data gathered in the previous phase, (ii) discussions with the company team involved in the implementations, (iii) a final meeting with this team, to present and discuss the results, and (iv) insights from the literature. The outcome is a P&C model founded on an appraisal of what does and does not work about the LPS and on the results of complementary Lean Philosophy implementations. This model requires implementation and evaluation.

Triangulation was employed as a strategy to enhance the reliability and validity of the research findings by using multiple sources of evidence. This approach involved collecting data from various sources in order to get a comprehensive understanding of the phenomenon under investigation. The data collection involved mostly (i) presentation and discussion of results and proposals in workshops, sometimes with training on LPS and Lean Philosophy concepts and principles; (ii) observation of production, P&C meetings, and training program; (iii) participation in the development of P&C tools in meetings; (iv) interviews with plant manager, continuous improvement manager, P&C coordinator and analysts, production supervisors, designers, construction manager and construction coordinator; (v) analysis of documents, such as long-, medium- and short-term P&C spreadsheets, assembly orders and activity check-in/out databases, indicators, and management charts. The sources of evidence used in this study are presented in Table 1.

Table 1: Data collection

PHASE	SOURCES OF EVIDENCE	HOURS
UNDERSTANDING	Workshop (1); direct observations; open interviews; document analysis; photographic records; field notebook notes.	9 visits (30 hours); 1 meeting (1 hour).
DEVELOPMENT	Workshops (7); participant and direct observations; open and semi-structured interviews; document analysis; photographic records; field notebook notes.	26 visits (45 hours); 7 meetings (18,5 hours); 13 interviews (16,5 hours).

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The study was undertaken in a Brazilian MC company, located in southern Brazil. The company delivers complete modular building projects: it designs modules and construction (architecture, structure, electrical, plumbing), manufactures modules and components, transports them, and delivers the completed project (module installation and on-site activities). Each project is unique, as the client often chooses specific layouts and the finishings. During this research study, the company was transitioning from artisanal to industrialized processes in the manufacturing system, strongly based on the Lean Philosophy.

The factory operates as a set of "mini-factories", which are in charge of manufacturing the modules themselves or components (panels, floors, ceilings, and concrete furniture, for example). The mini-factory analyzed in this research comprises assembly and finishing activities, producing customized modules for the educational, healthcare, corporate, and residential segments. It was a static production line: modules remained stationary while different crews move, achieving an average throughput time of about 11 days, delivering an average of 3 modules per day. This product has three main variants: with bathroom, without bathroom, and without panels (no walls), which in turn have modules that also vary in workload. At the beginning of this study, a large share of manufacturing activities was similar to conventional construction, such as drywall, painting, electrical and plumbing installations, waterproofing, porcelain tile installation, and window frames.

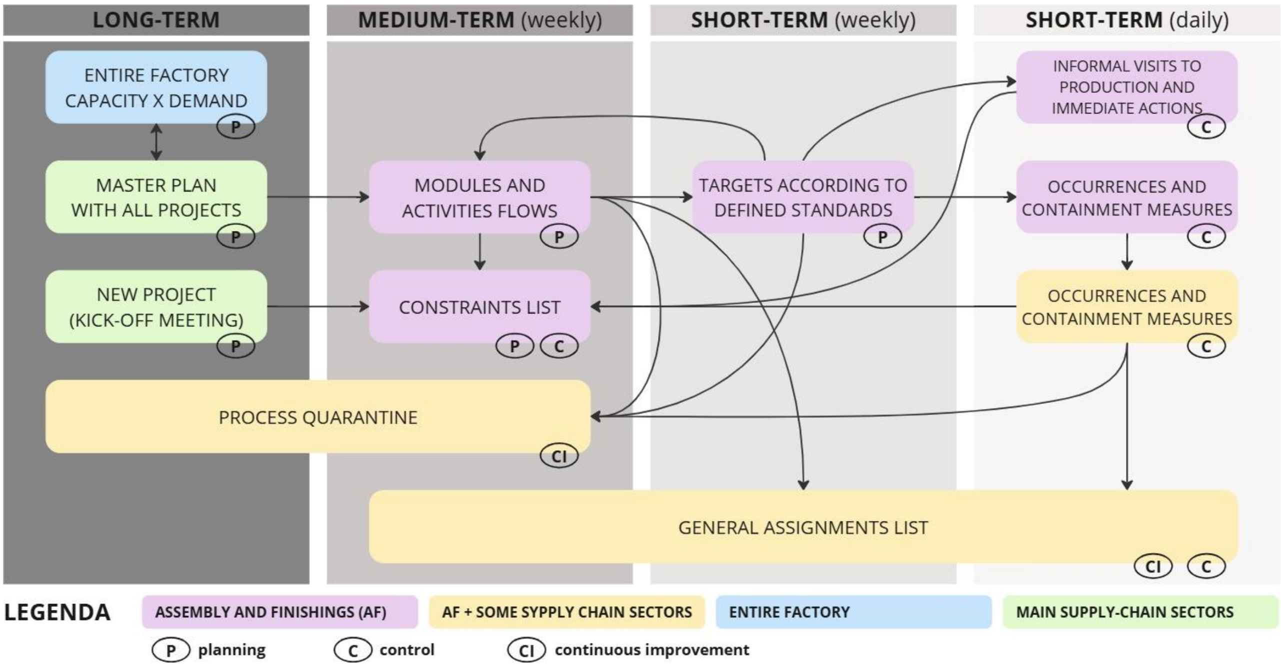
3. Results and Discussions

Figure 1 provides an overview of the proposed P&C model, based on the LPS and TP, as well as on the results observed after implementation and discussions with the team. The model follows a long-, medium-, and short-term hierarchical structure, as in the LPS, and highlights the scope of decisions at each instance and the connections between them. At several points, decision-making must involve multiple mini-factories and sectors of the supply chain, even when the primary focus remains on the module assembly and finishing mini-factory (the focus of this research), as shown in Figure 1. This involvement of other parts is necessary because, at times, there is strong interdependence and a need for collaboration to ensure good performance of the production line under study, as well as the system as a whole. Furthermore, sometimes the analyses focus on a single project and at other times on overall production. The model also highlights the different functions of each decision: planning (P), control (C), or continuous improvement (CI).

In the **long-term instance**, decisions are made with the primary goal of leveling factory production across all mini-factories, encompassing both component manufacturing and module assembly and finishing. To this end, potential demands and factory capacity are reconciled through simulations to smooth production fluctuations. These definitions are based on discussions with other sectors of the supply chain, considering all projects, so that goals are aligned and interdependencies are understood (“master plan with all projects” in Figure 1). These informations about goals and interdependencies can be made explicit through visual planning tools, fostering collaboration among stakeholders.

Due to the company’s business model, which offers product customization to clients, a collaborative effort among sectors is required to identify constraints and critical resources and closely monitor these definitions. For such monitoring, the constraints list (Figure 1) must be easily accessible and highly visible. This collaborative effort should begin at the kick-off meeting (Figure 1), focusing on this new project. Critical resources are understood as (i) those not common to the manufacturing of modules concerning all projects, but which arise from product customization, or (ii) those that frequently cause trouble. These items refer not only to materials, but also to, for example, labor, techniques, equipment, and tools potentially required for the manufacturing of components or modules assembly and finishing. Given the short lead time between contract signing and final delivery, even a small delay or insufficiency in these items results in reduced quality, rework, increased on-site activities, higher costs, and delays in final delivery.

Figure 1: Planning and control model for MC factories



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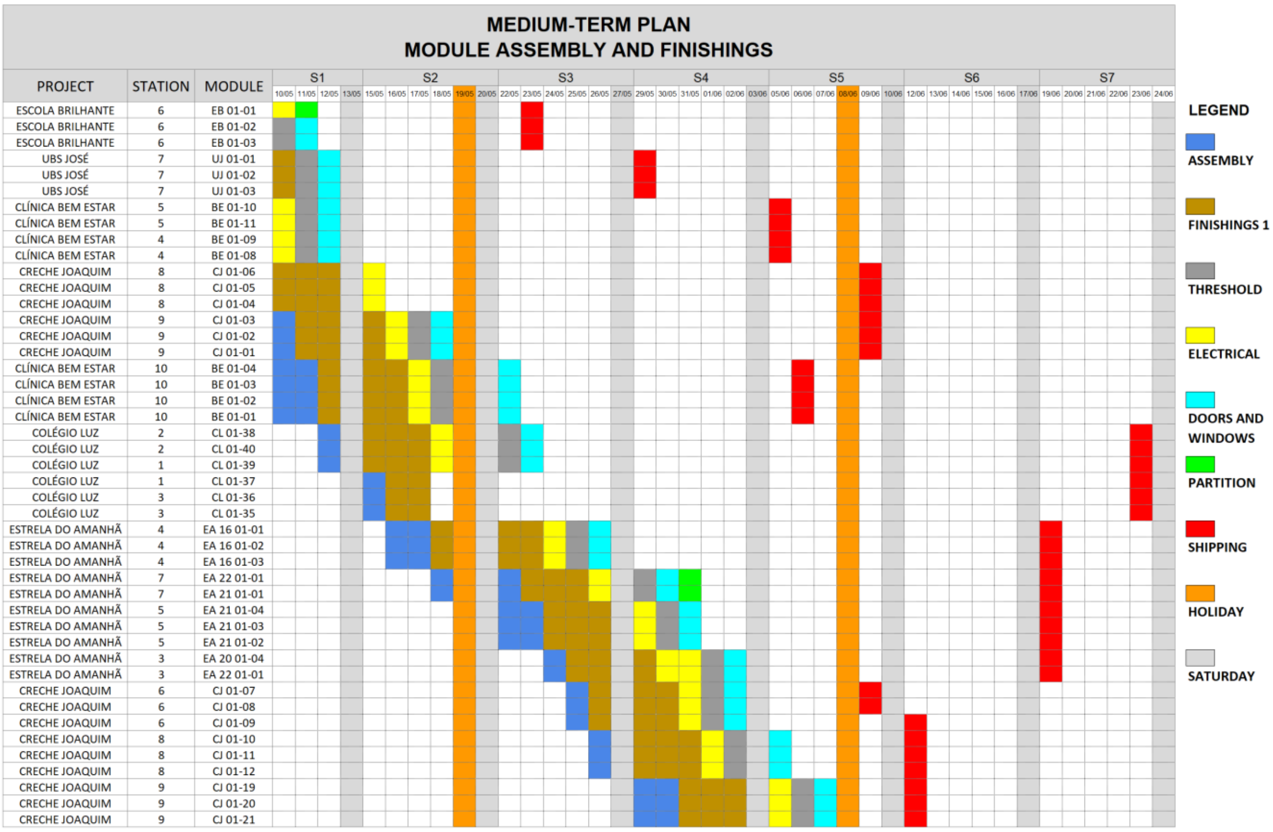
After the initial analysis from the kick-off meeting, other constraints related to production in general (concerning modules of all projects) may arise in production P&C routines (such as in weekly and daily meetings) or from formal and informal daily occurrences. These must also be incorporated into the constraints list, with easy access, high visibility, and close monitoring, to be used in the various meetings. The model presents the different moments in which constraints may arise, composing the "constraints list" (Figure 1).

The challenge of balancing the production of modules with significant variations in workload can be addressed by defining batches composed of the association of more than one module (Figure 2), which together result in batches with more similar workloads, similar to the attempts of Rodrigues (2006) and Tommelein (2017) to create repetition in production. Alongside this, standards for executing this generic batch must be defined, structuring the work. Initial standards may be defined using estimates from the experience of supervisors and operators, and subsequently go through refinement cycles based on real quantitative data. Thus, production can be visualized as a flow, analogous to a train with its wagons, with the help of a location-based plan where the modules compose its location structure. These definitions are represented as "modules and activities flows" in Figure 1, composing the **medium-term instance**.

In the study, this standardization, or work structuring (Tommelein et al., 2024), initially referred to (i) defining the sequence of activities (for a generic batch of modules) and (ii) grouping these activities per day (i.e., day 3: electrical installation + fiberglass + studs and tracks + OSB wall panels; day 4: gypsum boards in walls and ceiling). An extract of the location-based plan used by the company team during the study is presented in Figure

2, which was the medium-term plan. The plan contains (i) the module batches, (ii) the sequence in which the modules will be produced, (iii) the station the module will be produced, which is static, (iv) the defined standards (the sequence of wagons), (v) the activity flow, (vi) the multiple projects, and (vii) the shipping dates. This location-based planning enabled production supervisors to observe the interdependencies between their crews and the required production rate, taking into account the contract shipping dates. It used to be previously prepared based on the defined standards, and it was strongly used in weekly meetings to align and confirm the following week's commitments among supervisors, also considering what had been completed in the previous week.

Figure 2: Extract of the medium-term plan (location-based plan)



PROJECT	STATION	MODULE
ESCOLA BRILHANTE	6	EB 01-01
ESCOLA BRILHANTE	6	EB 01-02
ESCOLA BRILHANTE	6	EB 01-03
UBS JOSÉ	7	UJ 01-01
UBS JOSÉ	7	UJ 01-02
UBS JOSÉ	7	UJ 01-03
CLÍNICA BEM ESTAR	5	BE 01-10
CLÍNICA BEM ESTAR	5	BE 01-11
CLÍNICA BEM ESTAR	4	BE 01-09
CLÍNICA BEM ESTAR	4	BE 01-08
CRECHE JOAQUIM	8	CJ 01-06
CRECHE JOAQUIM	8	CJ 01-05
CRECHE JOAQUIM	8	CJ 01-04
CRECHE JOAQUIM	9	CJ 01-03
CRECHE JOAQUIM	9	CJ 01-02
CRECHE JOAQUIM	9	CJ 01-01
CLÍNICA BEM ESTAR	10	BE 01-04
CLÍNICA BEM ESTAR	10	BE 01-03
CLÍNICA BEM ESTAR	10	BE 01-02
CLÍNICA BEM ESTAR	10	BE 01-01
COLÉGIO LUZ	2	CL 01-38
COLÉGIO LUZ	2	CL 01-40
COLÉGIO LUZ	1	CL 01-39
COLÉGIO LUZ	1	CL 01-37
COLÉGIO LUZ	3	CL 01-36
COLÉGIO LUZ	3	CL 01-35
ESTRELA DO AMANHÃ	4	EA 16 01-01
ESTRELA DO AMANHÃ	4	EA 16 01-02
ESTRELA DO AMANHÃ	4	EA 16 01-03
ESTRELA DO AMANHÃ	7	EA 22 01-01
ESTRELA DO AMANHÃ	7	EA 21 01-01
ESTRELA DO AMANHÃ	5	EA 21 01-04
ESTRELA DO AMANHÃ	5	EA 21 01-03
ESTRELA DO AMANHÃ	5	EA 21 01-02
ESTRELA DO AMANHÃ	3	EA 20 01-04
ESTRELA DO AMANHÃ	3	EA 22 01-01
CRECHE JOAQUIM	6	CJ 01-07
CRECHE JOAQUIM	6	CJ 01-08
CRECHE JOAQUIM	6	CJ 01-09
CRECHE JOAQUIM	8	CJ 01-10
CRECHE JOAQUIM	8	CJ 01-11
CRECHE JOAQUIM	8	CJ 01-12
CRECHE JOAQUIM	9	CJ 01-19
CRECHE JOAQUIM	9	CJ 01-20
CRECHE JOAQUIM	9	CJ 01-21

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Thus, defining batches and daily groups of activities favored production synchronization, similar to what Bonesi-De Luca et al. (2024) and Formoso et al. (2025) proposed for conventional construction. Bonesi-De Luca et al. (2024) sought to synchronize a set of activities with a five-day cycle time each, also supported by a location-based planning. To implement this plan, Bonesi-De Luca et al. (2024) detailed what should occur within each activity's five-day cycle time by (i) allocating space (product) among the crew and (ii) defining their standard execution path. That level of breakdown was not within the scope of the present study, due to the low production stability at that time. In its context, the team had greater flexibility in allocating resources during the one-day cycle time to handle variability, and was also allowed for recovery throughout the week. However, in subsequent phases, with more production stability and more data available, more detailed standards of how work should occur within each daily group of activities could be formalized.

Considering the defined standards and the repetitive nature of manufacturing, it is unnecessary to create an entirely new plan for each **short-term** cycle, as it happens in conventional construction at LPS. The weekly alignment among production supervisors, based on the location-based plan, which includes the defined standards, results more automatically in each crew's targets for the short-term cycle, and for the standards-cycle times. These definitions are presented in the model as "targets according to defined standards".

The defined standards should also directly support production control, with occurrences being identified based on noncompletion of standard cycles. Daily monitoring results in control (C) and continuous improvement (CI) actions, which arise formally or informally (i.e., "immediate actions", "containment measures", "constraints", "general assignments", and "process quarantine" in Figure 1), mostly from the identification of occurrences. The differentiation among these actions is based on (i) the way in which the problem is affecting production, i.e., interrupting it or not, and (ii) the effort required to develop a solution, and it was proposed to ensure continuous improvement and consequently increased stability. For instance, the suggested "process quarantine" is proposed as a tool that develops the more complex continuous improvement projects and limits the quantity of these projects in progress, prioritizing the most important and ensuring control; these projects arise mainly from the analysis of causes for noncompletion and insights that emerge in weekly and daily meetings. The "containment measures", in turn, are urgent plans, formalized mainly in daily meetings, to solve a production occurrence that, until executed, keeps an outstanding issue or stoppage in production. The "immediate actions" arise from informal visits to the production (Figure 1), while an *andon* system is not implemented.

The LPS's commitment plan (short-term) was, in a way, replaced by the collaborative definition of standards with supervisors, which should be refined and further detailed by themselves as production stability increases and real data are available. This commitment was later confirmed in each weekly alignment of the location-based plan, when considering the completion of activities and the deadlines. The sequence of modules to be produced can be adjusted according to the constraints' removal, so that only modules that can be completed without interruptions (modules without constraints) enter production, similar to the LPS's shielding production mechanism. Thus, the **short-term instance** focuses mainly on continuous improvement and production control, while flow management and WIP control occur one step earlier.

Finally, based on the development of the P&C model, it is suggested that, instead of the LPS's weekly PPC (percent plan complete), each crew be controlled based on the defined production rate. For example, if the rate is three modules per day, all crews should have this same rate as a control unit: each crew must complete its daily activities on three modules. This rate can be weekly, daily, or hourly, for example, as production stability increases. However, it is emphasized that using a week as a control unit to identify noncompletion reasons proved too long. The nature of this manufacturing demanded faster corrective actions.

4. Conclusions

This study presents a preliminary version of a P&C model for MC factories that (i) produce a customizable product, (ii) perform activities similar to those of conventional construction, or (iii) are transitioning from a more artisanal production system to a more industrialized one. The model defines the scope of decisions for each P&C level, which can be regarded as prescriptive knowledge that can be used by similar factories to achieve stability and manage their complexity.

Furthermore, it was possible to explore the mechanisms of LPS in the manufacturing context, as well as its complementarity with TP. It must be pointed out that work structuring and the definition of standards play a fundamental role in stabilizing and synchronizing production, and reduce the relevance of the traditional short-term plans; thus, the commitment plan of LPS occurs more effectively during the collaborative definition of standards. The shielding mechanism of LPS works by allowing only modules without constraints to enter production. The systematic constraint analysis of LPS, in turn, is extremely important for managing the resources arising from product customization.

The standardization, through TP, drives further the effort of achieving stability, which in turn provides capacity and reliability for a more refined subsequent standardization, and so on. In addition to defining targets, standardization allows for greater understanding of the system's production capacity. Stability, in turn, is developed as the system continually improves its processes to meet these targets and resource availability.

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CONCEPTUALIZATION OF MASS CUSTOMIZATION AND ITS RELATIONSHIP TO EMERGENCY HOUSING AFTER A DISASTER. CASE STUDY IN SANTA JUANA, CHILE.

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ABSTRACT

Socio-natural disasters are becoming increasingly common worldwide, significantly increasing in the last 20 years. At the local level, Chile is one of the OECD countries most exposed to these disasters. Although emergency housing has been widely studied, there is still a lack of research focused on methods for developing housing that meaningfully addresses user needs. This research aims to explore potential alignments between concepts derived from mass customization and emergency housing towards developing more appropriate housing solutions. The research was conducted using a qualitative methodology, linking the concepts of mass customization presented in the literature with a case study of an emergency home delivered in Santa Juana, Chile. The results show a clear relationship between key concepts of mass customization theory and the case study. This theoretical and practical connection demonstrates the potential advantages of addressing temporary accommodation through a mass customization lens including cost and time reduction, and a better capacity to meet user, thereby advancing the provision of adequate emergency housing after a disaster.

Keywords: Transitional housing; Mass customization; Mass personalization

1. Introduction

At the global level, socio-natural disasters have increased by 1.7 times from 2000 to 2019 compared to that from 1980 to 1999 (UN, 2020). In Chile, 54% of the population and 12.9% of the territory are at risk of being affected by three or more threats (Diley, 2005).

In this context, it becomes imperative to pay attention to the development of emergency housing, also called temporary housing or transient housing in literature (Pezica, Cutini, Souza, 2021), which aims to allow the return to normal daily activities in a temporary location. In the provision of emergency housing, attending to the objectives of reduced costs, rapid response, and abundant coverage can be in contrast to giving space for the attention of particular needs and interests of affected families. This, in contrast, is a problem already solved in other industries through mass customization, but in the case of emergency housing is scarcely investigated.

The concept of mass customization was introduced by Toffler (1970), who states that they are "the systems and technologies of the future (...) capable of offering variety and individuality of products almost without additional costs", and currently Conte, Echeveste, Formoso, Bazzan (2022) define mass customization such as *"a strategy to deliver custom products to costs and delivery times similar to mass production."*

Understanding the potential of mass customization to meet user needs, without losing the attributes of industrialization, is the initial objective of this study, which seeks to understand the relationship between the concepts of mass customization and the possible response to emergency housing needs. Considering the 3 stages of a home proposed by Formoso, Tillmann, and Hentshke (2022): (i) Design, (ii) Construction, and (iii) Use of the home. The research focuses its analysis on the last of the stages, with a case of emergency housing in use, to investigate the modifications made and how they can be linked to mass customization. The particular case study corresponds to a single emergency home delivered due to a forest fire in Santa Juana, Chile, and serves as a practical tool to reflect the theoretical connection with the concept of mass customization.

2. Method

The research was conducted using a qualitative methodology in two phases: (1) theoretical analysis, and (2) practical connection with a case study.

In the first, theoretical phase, a review of key books and articles on the concepts of mass customization was conducted, followed by a case study. Regarding the concept of mass customization, the literature review included articles from the last five years, registered in the SCOPUS databases, using the following search string: "mass customization" AND "architecture" OR "mass customization" AND "architecture" OR "mass customization" AND "architecture"

An initial filter was used to select articles that addressed the topics of architecture and mass customization, considering the architectural filter, given the importance of the architect's role as a promoter of a mass customization methodology. Subsequently, articles related to relevant mass customization concepts cited in the initial articles were added. From the literature on mass customization, concepts related to this topic that could be related to responses to the characteristics of emergency housing were extracted, and a table was created with these concepts, definitions, and citations.

The second, practical, stage focused on exploring conceptual relationships with a practical case of emergency housing built in the rural area of Santa Juana, a town of 13,000 inhabitants in south-central

Chile. The delivery of this emergency housing was a result of the 2023 forest fire that affected 55.14% of the territory.

The floor plans of the delivered homes were reviewed, using information provided by the public and private organizations that managed the housing provision. A field visit was subsequently conducted, gathering information on the architectural modifications made by the users through drawings, diagrams, and photographs. With these inputs, a participation form was created that included a graphic description of the original emergency housing and the modifications made by the users.

The case study presented an analysis of the relationships between the concepts of mass customization and how these were reflected in the case study.

3. Results

3.1 Concepts

The proposed concepts characteristic of Mass Customization, extracted from the literature review, are presented below. The specific concepts of industrial development for products designed and manufactured under this conceptual framework, which were reiterated, were recorded and grouped into the following definitions:

Massivity: As one of the core ideas embedded in the term itself, personalization is a foundational concept of Mass Personalization and one of its two main pillars (Monizza, Matt, 2022). It relates to the scale of the target customer market (Rauch, Dallasega, 2017), which facilitates maintaining a low unit manufacturing cost (Anattasakul, Slama, Demirel, 2023).

Customizable: Defined as an approach to meet different customer needs in mass production (Rauch, Dallasega, 2017), cluster analysis can be used as a tool to determine everyday needs among consumers by packaging customization alternatives into groups (Elmogahzy, 2019).

Product platforms: This is the multipurpose framework that allows for accommodating and coupling different optional elements of the product (Mohamed, Carbone, 2022), allowing for progressive interaction with it over time. This platform is part of the essence that defines a particular product and enable the user to combine different options to create a personalized procuct (Monizza, Matt, 2022).

Optional product elements: These are elements that are coupled to the base platform with the aim of personalizing objects, creating a fit between the customer and the product (Anattasakul, Slama, Demirel, 2023). These optional elements must be standard components produced in large quantities and with simple joining rules (Mohamed, Carbone, 2022), allowing for many combinations with the base platform.

Process flexibility: refers to a flexible and reconfigurable production system (Monizza, Matt, 2022), capable of generating diverse products (Mohamed, Carbone, 2022). This production process flexibility allows for manufacturing everything from platforms to various optional elements to be attached.

Product flexibility: This is understood as the product characteristic that allows for more precise and specific adaptation to the user. At the same time, mass customization provides initial adaptation through optional elements incorporated into the platform, which represents an adaptation to customer needs. Product flexibility refers to the possibility of customization once in use, allowing it to meet specific needs at a family or personal level. As Anattasakul, Slama, and Demirel (2023) demonstrate, mass customization provides a certain degree of flexibility and customization; however, products must be adapted to the more specific needs of customers. Mohamed and Carbone (2022) complement this statement by indicating that product flexibility refers to product variations throughout its use.

Prefabricated modularity:

A key feature is the modularity of prefabricated products, allowing for successful combinability between the base platform and optional elements. According to Mohamed Carbone (2022), standard components produced and prefabricated off-site can be combined if there is precise modulation and simple interconnection rules for joining them. This is reinforced by Elmogahzy (2019), who points out that one of the mass customization tools to meet customer needs is the modularization of products.

Interaction in Design and Construction: For mass customization, interaction between the customer, designer, and manufacturer is essential, building a complementary relationship through direct or indirect communication (Mohamed, Carbone, 2022). Through this interaction, customers can select attributes from predefined characteristics to design their individualized product (Monizza, Matt, 2022), which meets part of their needs. The links must be between users, designers, and manufacturers. They must also allow for interaction between the object and the user during the construction stage.

Digital design and manufacturing: Understood as a tool for mass customization, enabling interaction between the client, designer, and manufacturer during the design and construction stages. Monizza, Matt (2022) points out this when indicating that customization is based on the evolution and interconnection of all computer-based technologies. This is in line with what Abdulmajeed, Agkathidis, Dounas, Lombardi (2023) stated when pointing out that mass customization occupies digital design and manufacturing and, in this way, allows buyers to select their designs.

3.2 Case

The case study and its connection to the Mass Personalization concepts are presented below. This case study corresponds to one of the emergency housing units built following the 2023 forest fire in Santa Juana, Chile. The housing unit is located in South America at coordinates: 37°10'00"S 72°56'00"W. The area is 731 square kilometers, with a population of 13,749, and a density of 18.8 inhabitants per square kilometer.

The disaster was a forest fire that destroyed a large part of the rural area of Santa Juana, including homes, warehouses, facilities, and plantations, among other items.

Following the disaster, the Chilean government authorized the delivery of 383 emergency housing units to the victims, which were built on the same damaged land. The area's rural nature allowed for the construction of housing in the same areas where people lived before the fire, as these were large plots of land typically housed houses, warehouses, and space for growing crops and raising animals.

In Chile, emergency housing is understood as a structure that "provides a short-term and temporary solution to the habitability problem of one or more people following a catastrophic event that renders their home unusable." It also has minimum standards that include "a basic electrical installation and may or may not include a bathroom," and "a minimum of 4.5 m2 per person, which provides thermal comfort, good ventilation, and protection from the rigors of the climate, and guarantees privacy, safety, and health, while allowing for essential domestic activities and those that support livelihoods" (SENAPRED, 2023). The case study of the emergency housing provided by the government is a 24-square-meter home with an attached bathroom module. It is built with panel walls (planar structure) made of wood panels on both the exterior and interior sides, and a core containing thermal insulation. The home is floored with wood panels, supported by wooden pile foundations, and has a metal-sheet roof. The homes are prefabricated off-site, transported in panels by truck, and built by local construction companies.

Initially, the home is delivered with two rooms: one multipurpose (kitchen, dining room, living room, and bedroom) and the other, the attached bathroom.

The case study is located next to a road in a rural area. The land is flat (where the home is located) and has a slope adjacent to it (where plants are grown) (Figures 1 and 2).

Figure 1: Location

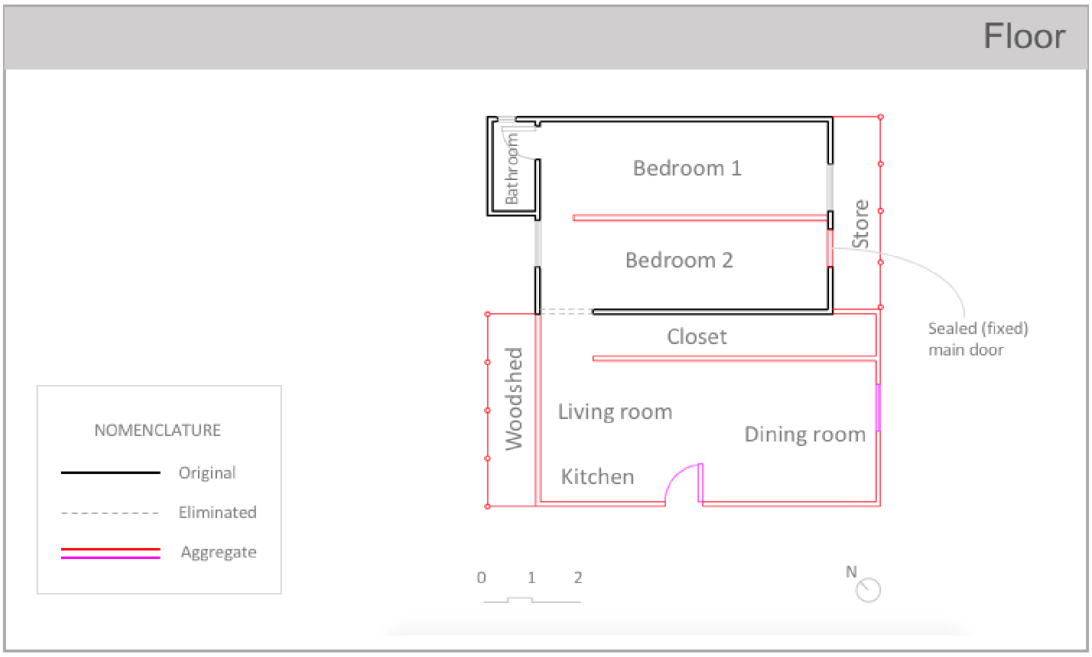
Font: Created by the authors based on Google Earth

Figure 2: Context

Font: Author's archive photo

The house was surveyed after a year of use, recording the modifications made by the inhabitants themselves. The floor plan of the house is shown in Figure 3, with the original house indicated in black lines and the changes made in red.

Figure 3: Housing floor



Font: Created by the authors

Although the housing unit is not designed and built under the logic of Mass Customization, this analysis proposes to identify the potential for linking the concepts of mass customization with emergency housing, after one year of use, identifying that:

"Mass customization" has the potential to improve the quality of the houses while maintaining short lead times within cost, given that this disaster required the rapid delivery of 383 emergency homes at the same time. Furthermore, it can be seen that the materials used for the construction of the homes are local, such as the wood panels made from products from the same country, which also contributes to shorter response times.

The "customizable" aspect of mass customization can be partially seen in the two alternatives provided by the Chilean government for officially modifying the home: the option of incorporating a bathroom as part of the initial stage, and the second option is the partition wall between bedroom 1 and bedroom 2, which was provided only upon request by the home's users. While it may seem limited, it can be interpreted as the initial seed for customization to emerge, identifying the multipurpose space provided as a possible "base platform" and the bathroom and partition alternatives as "optional elements."

No further "optional elements" were identified. The necessary adaptations of the emergency home begin to be added through self-construction by the occupants themselves, building extra spaces for the kitchen, living room, dining room, closet, woodshed, and storage room. This means that the climatically relevant elements, such as the woodshed and outdoor storage room, are self-constructed, which function as intermediate spaces to prevent direct rain from entering the openings. This also highlights the capacity of unskilled labor among the inhabitants to make modifications, even though the home is not designed for this purpose.

The "process flexibility" in this case study is not evident, given that the homes delivered by the construction company are all identical and, except for the bathroom and partition alternative, no further clear modifications can be done to the design or with the manufacturer. This evidences the lack of a product platform that may allow for collaboration between the user, designer, and factory.

Regarding "product flexibility," since this is a panel-based home, which combines the structure, exterior cladding, insulation, and interior cladding, all in a single element, it is challenging to make modifications without altering the entire unit. For this reason, the case study does not offer the ability to achieve a design that is versatile over time.

The "prefabricated modularity" is evident in paneled construction, where the building is modular in relation to the wood panels, avoiding overlaps and contributing to sustainability. However, there is no clear modular strategy to further accommodate the spatial and functional needs of the users. Therefore, this type of modularity does not contribute to housing adaptability over time.

Finally, the analysis of the case study does not show “interaction in design and construction" or "digital design and manufacturing." Therefore, user participation is restricted to self-built modifications during the use phase. However, there is no possibility of influencing the early design and construction stages. Therefore, adjustments and prioritization of necessary functions, climatic and cultural relevance, cannot be made, as evidenced by the users' subsequent arrangements to accommodate the homes to their needs and preferences.

4. Discussion

Emergency housing responses must be rapid and cost-effective to reach the large numbers of people that can be affected by a natural disaster. However, this response must be balanced and capable of addressing their needs and preferences, in line with the objectives set by Davis (2015), Murao (2010), Valent (2019), and Nappi (2015). In the case of Chile, the country of the case study, the government also sets this as an objective stating that emergency housing must *"guarantee privacy, safety, and health"* (SENAPRED, 2023). Further, addressing the different needs and preferences of people with housing is in line with architecture's ability to contribute to the well-being of its inhabitants (Chowdhury, Noguchi, Doloi, 2023).

Mass customization opens up an opportunity to achieve balance; Speed, cost, and attention to the needs of occupants in emergency housing, according to the analysis of this research. In this way, the latent potential of people affected by disasters to informally reconstruct their context during the housing use phase can be leveraged, given their labor capacity and available time (Carta Humanitaria, 2011) (De Masi, de Rossi, Gigante, Ruggiero, Vanoli, 2023).

The case study highlights how residents can double the surface area of their homes through self-construction. This suggests that Mass Customization could be part of participatory design and construction approaches, allowing people to incorporate their needs and preferences throughout the design and construction phases.

Mass Customization allows people's needs to be addressed gradually, through three levels of intervention. (i) First, the base platform covers the product's essential needs, such as an initial emergency housing module (chassis) that offers a quick and economical solution to the most basic needs. (ii) The second level introduces optional elements that users can choose from, thus addressing the more specific needs of groups of people. This aligns with Pine's (1993) idea that satisfying each consumer does not imply satisfying each individual separately, and is complemented by Elmogahzy's (2019) recommendation that marketing analysts identify common needs through cluster analysis. In terms of housing, this is pointed out by Noguchi (2004) and Tseng (2010), indicating that the key to customization is to identify patterns of user needs and associate them with product families. (iii) The third level of intervention is that of the users. This potential for self-construction is evident in the case study, but for it to function formally and optimally, it must be enabled by a flexible design.

Given the limited resources after a catastrophe and the pressure of time, phasing the emergency housing response can serve to make the intervention of central public agencies and non-governmental organizations more efficient, and meet the needs of users, thus following the recommendations of Sphere (2018).

5. Conclusions

This article investigates potential links between the needs of emergency housing and the capabilities of Mass Customization. This is done through a literature review and case study analysis of an emergency housing project in Santa Juana, Chile. Based on the analysis, it can be concluded that Mass Customization can potentially contribute to providing better emergency housing through rapid coverage, reduced costs, while incorporating the needs of those affected. Contributing to the initial exploration of a Mass Customization strategy in Emergency Housing Designs following natural disasters.

The case study findings show a lack of attention to residents' needs, for example, regarding necessary functions. The case study also demonstrates residents' ability to address their needs through informal self-construction mechanisms. In this context, implementing mass customization principles in emergency housing may require digital interaction systems that enable user participation in the early stages of design and construction, while allowing for gradual changes throughout the building's lifespan.

Further research is envisioned to investigate the hierarchy of necessary functions of emergency housing in different cultural and climatic contexts in order to package these solutions into base platforms and optional elements to create relevant emergency housing. This also includes exploring new formal solutions that allow for flexibility and progression to incorporate responses to the most specific needs of residents.

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CHAPTER 3

BUILDING ENERGY, PERFORMANCE AND ADVANCED TECHNOLOGY

ASSESSING THE CONSISTENCY OF VISUAL COMFORT EVALUATION IN INDIAN GREEN BUILDING RATING SYSTEMS: A METRIC-BASED METHODOLOGICAL REVIEW

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ABSTRACT

Visual comfort is a key dimension of building design and is closely related to user satisfaction and the overall environmental quality of buildings. The study examines how visual comfort is represented and assessed in Indian green building rating systems and in educational institutions in particular. In examining the methodologies and criteria applied by various systems in evaluating visual comfort within built environments, metrics like Daylight Factor, Useful daylight illuminance (UDI), Uniformity Ratio, and Spatial Daylight Autonomy are reviewed with respect to the practicality of application, and its representation in existing ratings frameworks. The study compares the implications of different evaluation criteria and demonstrates how different understandings will influence design decisions for the very same space. This metric-focused investigation aims to identify commonalities, disparities, and best practices associated with visual comfort assessment. The study indicates the need for aligning visual comfort assessment with validated and context specific methods along with consistency in criteria and thresholds that are related to visual comfort across different rating framework, which will affect certification related performance outcomes and user experience. This study offers to build the discussion on building performance standards and calls for an appraisal of certification programs to better address well-being and to assist the decision-making process from the user perspective.

Keywords: Visual Comfort; Occupants; Indoor Environmental Quality; Green Building Rating System

1. Introduction

Green buildings are central to sustainable practice, especially within institutional campuses that, with wide range of users and varied programmatic needs, entail not only environmentally efficient but also human-centred design. Although the various certification programs like LEED, GRIHA, IGBC and Green Mark focus on energy savings and environmental performance, their effectiveness is more dependent on how efficiently they cater to occupants' well-being. Daylighting stands as a pivotal element in building design, offering a myriad of advantages encompassing energy conservation, visual comfort, physiological health, and psychological well-being (Baker et al., 2015). While the positive impacts of daylight are undeniable, the prevalence of visual discomfort poses a challenge, leading to disruptions and diminished focus among occupants, ultimately impeding productivity. To address this challenge, it is imperative to establish well-defined guidelines regarding the design of spaces, fenestrations, and shading devices, ensuring optimal lighting conditions within the space to mitigate undesirable effects.

Occupant visual comfort, rooted in individual satisfaction with the quality and quantity of light within their environment, becomes a crucial factor in assessing the success of daylighting strategies (Boyce et al., 2003). Green building rating tools around the world commonly address and incorporate Visual Comfort parameters within the Indoor Environmental Quality section of their frameworks, reflecting a global acknowledgment of its significance (U.S. Green Building Council, 2020). The expectation is that certified green buildings would offer significantly improved visual comfort, fostering greater occupant satisfaction and reduced health concerns compared to non-certified counterparts. Despite this widespread recognition, existing green building rating systems, such as IGBC, GRIHA, LEED, among others, primarily emphasize quantitative aspects of daylighting, including illuminance, Daylight Factor, Useful Daylight Illuminance, and Spatial Daylight Autonomy etc (IGBC, 2018). These benchmarks must be met for satisfying the criteria score for visual comfort in the green building rating process. This paper explores the divergence in these standards across rating systems within the same country and climate, emphasizing the need for a nuanced understanding of how these criteria differ. Moreover, the study underscores the significance of addressing qualitative aspects like glare, lighting distribution, and general visual comfort, as their neglect could lead to occupants experiencing discomfort even when quantitative requirements like UDI / sDA are met. While previous studies have explored occupant satisfaction with green buildings on a global scale (Frontczak et al., 2012), the examination of criteria for visual comfort among different green rating system with the Indian context remains unexplored. This research aims to bridge this gap by investigating existing criteria for visual comfort through a comparative study across diverse green building rating systems in India, shedding light on their variations and implications on occupants in educational settings. The study seeks to identify commonalities, disparities, and best practices related to visual comfort assessment by scrutinizing and comparing the methodologies and criteria applied by various green building rating schemes. The primary objective is to convey a thorough understanding of the intricate connection among visual comfort, occupant satisfaction, and green building practices. This aims to offer holistic guidance for the improvement of educational environments, particularly in terms of visual comfort.

2. Literature review

Daylighting, integral to educational building design, positively impacts occupants' health and contributes to a pleasant indoor environment. Adequate lighting levels are essential for efficient task performance, making it a crucial element in building design for energy savings, visual comfort, and overall well-being. Several studies in recent decades underscore the significance of daylighting, particularly in the design of educational buildings. The crucial role of daylighting in enhancing students' learning and productivity is emphasized, given that students spend a substantial amount of time engaged in intellectual activities within these spaces (Wu & Ng, 2003) . Nevertheless, the presence of visual discomfort poses a challenge, potentially leading to disruptions and a decrease in focus, directly impacting the learning experience. Visual comfort is defined as “a subjective condition of visual wellbeing induced by the visual environment” (Carlucci et al., 2015). It depends on environmental as well as personal factors such as the physiological conditions of the human eye, and can be assessed through parameters such as, Amount of light, Distribution of light in space, Prediction of glare risk for occupants.

While daylighting is beneficial, Excess of it can lead to issues like glare and increased internal heat. Common reliance on artificial lighting during daytime, often necessitated by dark internal blinds that are used for treating glare, contributes substantially to energy consumption, with schools spending nearly 50% of their electricity bills on artificial lighting, according to a BEE report (Bureau of Energy Efficiency, 2009). Daylight both activates and regulates circadian system, which in turn impacts our level of attentiveness and emotional state (Webb, 2006). Meanwhile, Inadequate exposure to daylight has been linked to health issues like fatigue, stress, and headaches, as well as academic concerns such as reduced productivity. Implementing energy-saving strategies and optimizing daylight usage can notably mitigate these challenges. Inadequate indoor environmental quality (IEQ) in lecture halls, can negatively impact their learning capacity and overall well-being (Haverinen-Shaughnessy et al., 2015). Effective daylighting in learning space has a substantial impact on students, whereas inadequate daylighting leads to discomfort and diminishes learning capacity (Ricciardi & Buratti, 2018). Several studies have indicated that improving visual comfort can indirectly enhance occupants' perception of thermal satisfaction. Daylighting is a crucial and valuable strategy in achieving visual comfort, directly contributing to energy savings by reducing energy consumption associated with artificial lighting (Fakhari et al., 2021).

A study conducted at two schools in Cambridge revealed that the mean illuminance was much higher than the recommended design illuminance (300-500 lux) in 88% of classrooms, and in 84% classrooms it reached levels beyond 2500 lux due to which visual comfort was found to be low. High illuminance in one area and low illuminance in another also caused visual discomfort (Winterbottom & Wilkins, 2009). The presence of windows, their orientation, and the quality of the view provided directly influence students' performance in completing creative tasks (Stone & Irvine, 1994). Thus, it is crucial to meticulously consider the design of spaces, fenestrations and shading devices in order to maintain optimum lighting conditions within the space, such that the undesirable visual effects are avoided or mitigated at the very least.

2.1 Metrics of Daylighting and Visual Comfort

Various guidelines exist to ensure optimal daylighting conditions in building design. Quantity of daylight measurement criteria can be broadly classified into Static/Illuminance-based metrics, including Illuminance and Daylight Factor, and Dynamic/Climate-based dynamic metrics (CBDM), encompassing Daylight Autonomy, Continuous Daylight Autonomy, Useful Daylight Illuminance, and Spatial Daylight Autonomy/Annual Sunlight Exposure.

Static Metrics like Illuminance and Daylight Factor (DF) measure the intensity and availability of daylight at a point, often referring to standards such as BIS SP 41 (1987), which prescribes 300 lux for lecture halls and daylight factor range of 1.9 to 3.8 for classroom desktops.

Climate - Based Dynamic Metrics provide a more dynamic understanding by assessing daylight performance over time. Daylight Autonomy (DA) represents the percentage of Occupied hours in a year when daylight illuminance exceeds a specified minimum threshold (GRIHA, 2019). Continuous

Daylight Autonomy (cDA) adopts the perspective that, even if daylight falls short of the specified standard, a partial contribution can still be advantageous for illuminating a space. Useful Daylight Illuminance (UDI) represents the portion of time in a year when the indoor horizontal illuminance at a specific point fall within a specified range. UDI is recommended for daylight assessment due to its inclusion of both upper and lower limits, allowing the categorization of light into scarce, adequate, and excessive, offering insights into potential glare and discomfort. Spatial Daylight Autonomy (sDA) is the percentage of floor area surpassing a designated illuminance level for a specific duration of occupied hours. Annual Sunlight Exposure (ASE) acts as the proxy for direct sunlight, offering insights into potential issues. The objective is to optimize sDA while simultaneously managing and limiting ASE.

Qualitative aspects of visual comfort, including glare control and lighting distribution, Color Temperature, Color Rendering, Spatial Layout ensures a more holistic approach to visual comfort, considering not only the quantity of light but also its quality and impact on the overall visual experience.

Uniformity, indicating the evenly spread daylight covering the entire work plane, is measured by the Uniformity Ratio (UR). This ratio is defined as the minimum illuminance divided by the average illuminance over a specific plane. Maintaining an ideal uniformity ratio, such as UR>0.6 on the task area (CIBSE), proves beneficial in preventing eye strain from constant adjustments to varying lighting conditions(Carlucci et al., 2015). According to NBC standards, a recommended UR>0.7 is suggested for Indian climatic conditions (NBC, 2016).

Glare, a phenomenon where a portion of the visual scene appears brighter than its surroundings, induces visual discomfort. Its effects are influenced by the position and viewing direction, considering factors like the size, position, and luminance of the glare source, as well as the surrounding luminance. Glare assessment metrics are integral for developing lighting systems that strike a balance between visual comfort and performance. These include Visual Comfort Probability (VCP), Daylight Glare Index (DGI), CIE Glare Index (CGI), Unified Glare Rating (UGR) and Discomfort Glare Probability (DGP). Research indicates that DGP consistently outperforms the Daylight Glare Index (DGI) and is therefore recommended as the most suitable glare metric (Costanzo et al., 2017; Jakubiec, 2014). Together, these metrics highlights that designing for visual comfort not just requires adequate lighting levels but also careful attention to uniformity, glare potential and user experience.

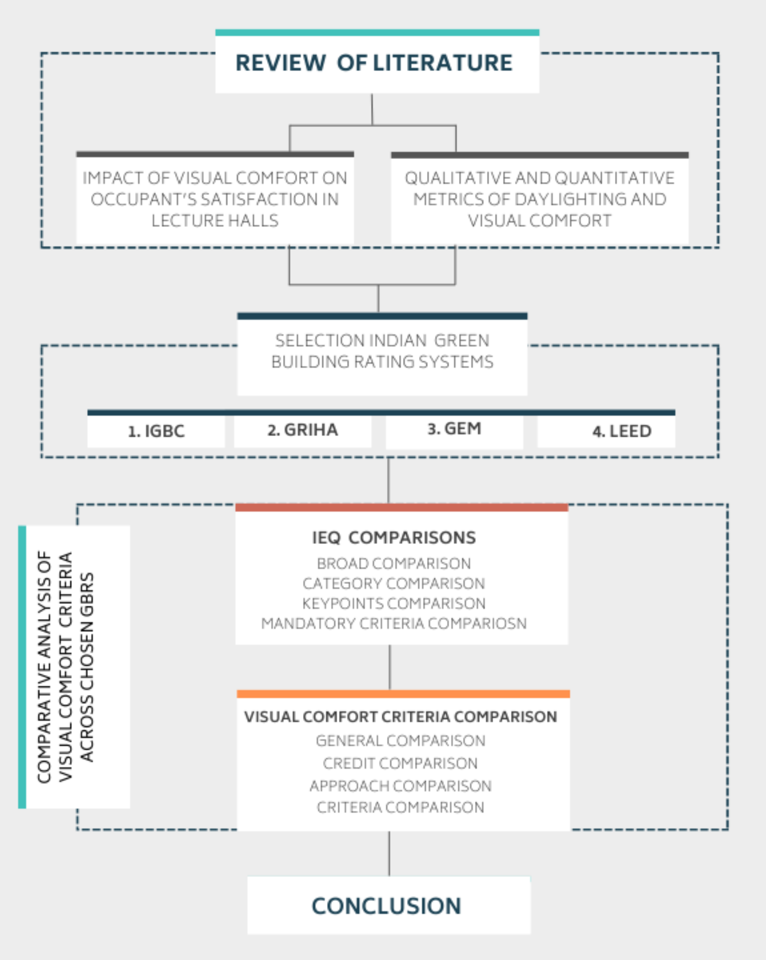
2.2 Adapting Visual Comfort Indices for the Design of Lecture Halls

Building planning and the design of lecture halls, along with fenestrations and shading devices, are interdependent, as each relies on the other (WWR, WFR, interior finishes, window size, glazing, sill height, depth, and angle of overhangs/louvers). Altering any of the above factors can have a substantial impact on the visual environment indoors, Supported by (Dang, n.d.) Dang's research in 2016, it was demonstrated that elevating the ceiling reflectance from 0.4 to 0.8 had a positive influence on Daylight Factor (DF) and uniformity. In adherence to Indian standards, the Energy Conservation Building Code (ECBC) 2017 suggests a maximum Window-to-Wall Ratio (WWR) of 40%, whereas the National Building Code (NBC) 2016 recommends a higher WWR, up to 60%. When assessing the visual performance of lecture halls in India, it is crucial to consider both qualitative and quantitative aspects of daylighting. This discrepancy may lead to confusion in deciding which standard to follow. Among the numerous available indices, examining various green rating systems and their visual comfort parameters becomes essential, given the widespread acceptance of green building frameworks and their reliance on globally recognized standards. This provides a framework for comparing different rating systems in India to comprehend visual comfort parameters effectively.

3. Materials and Methods

The Figure 1 here indicating the methodology for this paper for exploring the impact of Visual Comfort on Occupants and the Comparation of Different Green Building Rating Systems. The initial stage was devoted to a literature review, where the aim was to develop the groundwork for this study. At this stage two general areas were looked at: (i) the effects of visual comfort on occupant satisfaction, and (ii) the qualitative and the quantitative indicators that can be used to assess daylighting and visual comfort. The stage established the potential need for scientifically-determined indicators in rating systems.

Figure 1: Methodology.



Reference: Author

From this direction provided by the literature, the next stage examined the selection of Indian GBRS for assessment. Four GBRS were selected: IGBC, GRIHA, GEM, and LEED. These rating systems were selected as leading systems in the Indian GBRS landscape and also represented different approaches to indoor environmental quality (IEQ). The third stage, involved a comparative study of visual comfort criteria on the selected GBRS. The comparison took two levels: IEQ comparison, including broader level category comparison, identification of mandatory criteria, and key points of overlap and differences. Visual comfort comparisons, included general requirements for credit, credit structure, process, and metric identification. To finish, the conclusion distilled the key findings this study identified thematic consistencies and gaps for visual comfort assessment, and recommendations for harmonization and future rezoning of rating tools.

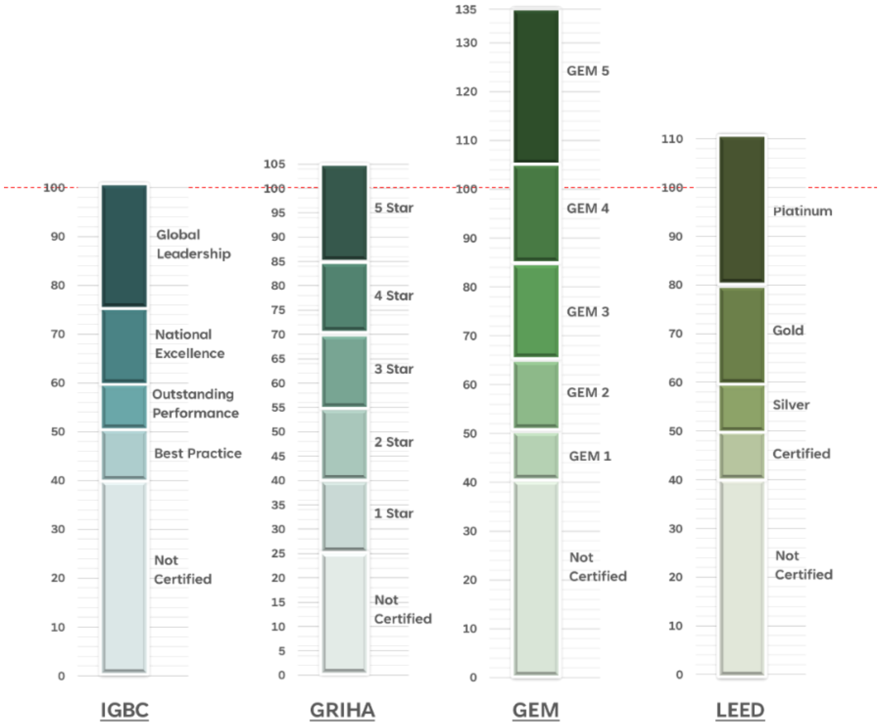
3.1 Selection of Green Building Rating Systems

Four Indian context rating system has been considered for this study. The green building rating systems used for the comparison are GRIHA, IGBC, LEED, and GEM SUSTAINABILITY. Table 1 presents the overview information on the selected GBRS. This research examines the most recent iterations of green building rating systems applicable to institutional structures (i.e., schools, colleges, universities), specifically focusing on certification frameworks designed for new construction projects.

Table 1: Overview Information on GBRSs

GBRS	Country of Origin	Name of the Manual	Version	Year of Publication	Founder/ Organisation	New Construction / Retrofit
IGBC - Indian Green Building Council (IGBC, 2018)	India	IGBC Green New Buildings Rating System	Version 3.0	2016	Indian Green Building Council	New Construction
GRIHA - Green Rating for Integrated Habitat Assessment (GRIHA, 2019)	India	GRIHA Volume 1	v.1	2019	TERI	New Construction
GEM - Green & Eco-Friendly Movement (ASSOCHAM, 2020)	India	GEM Reference Guide 2nd Edition	2nd Edition	2020	ASSOCHAM	New Construction
LEED - Leadership in Energy and Environmental Design (LEED v4.1, 2022)	United States (US)	Building Design and Construction	Version v4.1	2022	USGBC	New Construction

Figure 2: Level of Accreditation for selected GBRS



Reference: Author

The certification levels across various rating systems exhibit distinct criteria and scoring scales. Figure 2 shows the Level of Accreditation for selected GBRS. IGBC utilizes a scoring range out of 100, offering four certification levels: Best Practice (40-49), Outstanding Performance (50-59), National Excellence (60-74), and Global Leadership (75-100). GRIHA employs a star-based rating system, scored out of 105, with five levels: 1 Star (25-40), 2 Star (41-55), 3 Star (56-70), 4 Star (71-85), and 5 Star (86 and above). GEM Sustainability introduces five levels - GEM 1 to GEM 5 - scored out of 135, each corresponding to a different point range, from GEM 1 (40-49 points), GEM 2 (50-64 points), GEM 3 (65-84 points), GEM 4 (85-104 points), to GEM 5 (105 points or above). On the other hand, LEED offers certification levels based on a scale out of 110: Certified (40-49), Silver (50-59), Gold (60-79), and Platinum (80 and above). The minimum points / credits required to attain certification differs with each rating systems. Every green building framework adopts a distinct set of codes and standards as their benchmark for establishing required performance level. Consequently, a building certified in one rating system may achieve a different level or certification in another, highlighting the diverse benchmarks and criteria employed by each framework. This variability highlights the importance of considering the specific standards and criteria of each rating system when evaluating and comparing the environmental performance of buildings.

The comparative analysis approach, as indicated by (Li et al., 2017), is the appropriate method for evaluating the efficiency of green building frameworks. The comparison study can be at many levels—general, category and grouping, indicator, key-credit, and Economic, social, and environmental sustainability approach. This approach has been extensively recognised by scholars worldwide (Li et al., 2017; Varma & Palaniappan, 2019). The present investigation makes an effort to look at the assessment of visual comfort through the criteria and indicators established by the green building certification system in Indian context. An extensive overview of the different GBRS criteria indicated under Visual comfort and various Qualitative and quantiative visual comfort indices are presented.

4. Analysis and Discussion

4.1 Comparison of Indoor environment and Comfort Criteria accros selected GBRS

In green building rating systems, there are criteria that make up the system, those are categorized into distinct sections or chapters, encompassing Site Planning, Efficient Resource Use (energy, water, material, waste), Indoor Environment and Comfort, Building Operation and Maintenance, and Innovation Points. Each criterion is assigned points, and certain criteria are designated as mandatory or partially mandatory, while others offer credit points. Meeting these requirements makes a project eligible for accumulating points. The level of certification is then determined by the total number of points achieved, reflecting the project's commitment to sustainable practices and environmental considerations. Table 2 outlines Credits and Criteria in relation to indoor environment and comfort

Table 2: Credits and Criteria in relation to indoor environment and comfort

	IGBC	GRIHA	GEM SUSTAINABILITY	LEED
Total No. of Criterias	52	30	30	67
Total No. of Points	100	105	135	110
IEQ Section in GBRS	Indoor Environmental Quality	Occupant Comfort	No Category/ Section Segregated	Environmental Quality
No. of IEQ Criteria	10	3	3	12
Overall IEQ Points	12 Points	12 Points	15 Points	16 Points
Percentage in Total Weightage	12 %	11.4 %	11.1 %	14.5 %

In the category and grouping comparison, In the realm of green building certifications, the categorization and approach for visual comfort criteria vary across different rating systems. The Indian Green Building Council (IGBC) places visual comfort considerations within the "Indoor Environmental Quality" section, accounting for 12% of the overall weightage. GRIHA integrates these criteria into the "Occupant Comfort" chapter, emphasizing their significance in ensuring occupant well-being. GEM SUSTAINABILITY adopts a unique approach, focusing on achieving 30 principles, with Principle 18, Principle 26, and Principle 27 specifically addressing indoor environments and comfort. Meanwhile, LEED categorizes visual comfort criteria under the "Environmental Quality" section. Most green building system's organizational structure to achieve occupant comfort within built environments follows categorisation method.

In the Comparison of key credits/point, Indian Green Building Council (IGBC)'s Indoor Environmental Quality (IEQ) section encompasses 10 criteria, contributing 12 points out of the total 100 points in the overall rating system. This IEQ section holds a weightage of 12% in the assessment of green building. In the GRIHA framework, the "Occupant Comfort" section includes three IEQ criteria, contributing 12 points out of a total of 105 points, representing 11.4% of the overall weightage. GEM Sustainability integrates three principles directly linked to indoor and occupant comfort, accumulating 15 points out of the total 135, accounting for 11.1% of the total weights. On the other hand, LEED features 12 indicators under the "Environmental Quality" section, with a total of 16 points out of 110, reflecting a weightage of 14.5% in the overall rating system. Consequently, the LEED framework holds a higher weightage for IEQ considerations compared to the other green building rating systems.

In examining the mandatory criteria within the Indoor Environmental Quality (IEQ) sections of various green building rating systems, notable differences emerge. In the IGBC framework, two criteria, Minimum Fresh Air Ventilation and Tobacco Smoke Control, are designated as mandatory, while the remaining eight are credit-based system. GRIHA adopts a partly mandatory approach, with all the three criteria - Visual Comfort, Thermal and Acoustic Comfort, Indoor Air Quality - mandating a minimum requirement that can be exceeded based on achievement levels for higher points. Similarly, GEM SUSTAINABILITY follows a partly essential approach, ensuring the fulfillment of a baseline requirement across three principles related to indoor and occupant comfort. In contrast, LEED features three Prerequisite criteria - Basic indoor air quality efficiency, smoke from tobacco control, and optimum acoustic efficiency, with the other nine criteria being credit-based. In summary, IGBC and LEED employ a strictly mandated approach for certain criteria, while GRIHA and GEM Sustainability embrace a partially mandated model, emphasizing on achieving at least a minimum standard while allowing for further points based on higher achievement levels.

4.2 Comparative Analysis of Visual Comfort Criteria across different GBRS

In the comparison of visual comfort indicators within selected green building frameworks, distinctive approaches and weights are evident. Table 3 presents the visual comfort criteria across chosen GBRS.

The Indian Green Building Council (IGBC) incorporates two indicators, Daylighting and Outdoor Views, within its visual comfort criteria. These indicators are credit-based, contributing a total of 3 points, equivalent to 3% of the overall weightage. Specifically, Daylighting holds 2 points, while Outdoor Views contributes one point.

Table 3: Visual Comfort Criteria across different GBRS

IGBC			GRIHA			GEM			LEED		
Appraisal type	**Criteria**	**Points**	**Appraisal type**	**Criteria**	**Points**	**Appraisal type**	**Criteria**	**Points**	**Appraisal type**	**Criteria**	**Points**
Credit 2	Daylighting	2	Partly Mandador	Visual Comfort	4	Partly Mandatory	Optimised Use of Natural Light	6	Credit	Interior Lighting	2
Credit 3	Outdoor Views	1							Credit	Daylight	3
									Credit	Quality Views	1
Total Points		**3**	**Total Points**		**4**	**Total Points**		**6**	**Total Points**		**6**
Percentage in Total Weightage		**3.0%**	Percentage in Total Weightage		**3.8%**	Percentage in Total Weightage		**4.4%**	Percentage in Total Weightage		**5.5%**

Moving to the GRIHA framework, visual comfort is addressed under Criteria 10 within the Occupant Comfort and Well-being section. This criterion carries 4 points, constituting 3.8% of the overall weightage.Within the GEM sustainability framework, visual comfort is encapsulated in Principle 26, "Optimized Use of Natural Light," which encompasses 6 points, leading to 4.4% of the overall weightage. In LEED, visual comfort is evaluated through three credit-based indicators: Interior Lighting (2 points), Daylight (3 points), and Quality Views (1 point), totaling 6 points and representing 5.5% of the overall weightage.

Table 4: Comparison of daylighting analysis criteria across GBRS

GBRS	Daylighting analysis Criteria	Maximum Points / Credit
IGBC	>= 75% (1 point) or >= 95% (2 points) of occupied spaces should have daylight illuminance levels between 110 Lux and 2200 Lux.	**2**
GRIHA	Alternative 1: necessitates compliance with daylight autonomy (DA) through simulation, specifying meeting DA <3000 lux for 100% of annual analysis hours for all occupied spaces as mandatory, and achieving DA >300 lux for 25 % (mandatory), 50% (2 points), 60% (4 points) of annual analysis hours in all occupied spaces for additional points.	**4**
	Alternative 2: involves limiting the window-to-wall ratio (WWR) to 60%, ensuring minimum visual light transmittance (VLT) for vertical fenestration (0.27), restricting skylight roof ratio (SRR) to 5% and solar heat gain coefficient (SHGC) for skylights to 0.35, and setting maximum SHGC for vertical fenestration based on climate. Additionally, UDI compliance simulation mandates achieving illuminance levels between 100 Lux and 2000 Lux for minimum 40% (mandatory), 50% (2 points), 60% (4 points) of floor area for 90% of potential daylight time.	
GEM sustainability	GEM Sustainability aligns with ECBC 2017 Daylighting requirements, emphasizing useful daylight illuminance (UDI) and illuminance levels between 100 Lux and 2000 Lux for the minimum 40% (Essential), 60% (2 points), 80% (4 points) of floor area for 90% of potential daylit time.	**4**
LEED	Glare-control devices are mandatory for all options. Option 1: involves a simulation approach using spatial daylight autonomy (sDA300/50%) and annual sunlight exposure (ASE1000,250). The average sDA300/50% value for the regularly occupied floor area is at least 40% - 1 point or at least 55% - 2 points or at least 75% - 3 points	**3**
	Option 2: employs a simulation approach with illuminance calculations at specific times on a clear-sky day. Percentage of regularly occupied floor area with Illuminance levels between 300-3000 lux. for 55% (1 Point) or 75% (2 Points) or 90% (3 Points) regularly occupied floor area.	
	Option 3: adopts a measurement approach for illuminance calculations at specified times and months for the year.	

The methods employed for assessing visual comfort criteria in Green Building Rating Systems (GBRS) encompass two principal approaches: simulation-based and manual/measurement-based. In the simulation-based approach, the requirement involves submitting a simulation report generated by specialized software, along with other supporting documents, as evidence. On the other hand, the manual-based approach necessitates the measurement of visual comfort parameters at the designated work plane during specified times and dates. It is noteworthy that IGBC, LEED, and GEM Sustainability incorporate both simulation-based and manual approaches. In contrast, GRIHA tends to rely more heavily on the simulation approach for evaluating visual comfort criteria.

Overall, the comparison illustrates that visual comfort criteria hold significance, ranging from 3% to 5.5% of the total weightage in these green building rating systems. The significance of visual comfort in the evaluation of green buildings is undeniable, and the extent of its performance is indeed influenced by the specific indexes used by each framework. Additionally, the effectiveness of visual comfort strategies is further shaped by site-specific conditions, encompassing environmental factors, occupant behavior, shading strategies, fenestration design, and overall building and space design. Considering these variables in the assessment criteria underscores the holistic approach required to achieve optimal visual comfort tailored to the unique characteristics of each building and its surroundings. It emphasizes the need for frameworks to account for the diverse factors that impact visual comfort to promote more effective and contextually relevant sustainable building practices.

In the evaluation of daylighting analysis across selected green building rating systems, various criteria and indexes are employed to assess the effectiveness of daylight within the space. Table 4 shows the comparison of daylighting analysis criteria across GBRS. The IGBC framework focuses on achieving daylight illuminance levels between 110 Lux and 2200 Lux in occupied spaces, with options for scoring points based on the percentage of spaces meeting specific criteria. GRIHA offers two alternative simulation approaches: the first mandates compliance with daylight autonomy (DA) and the second assesses compliance using useful daylight illuminance (UDI) through computer simulation. Both approaches are partly mandated approach, wherein minimum level should be achieved in the alterative that is opted for simulation.GEM Sustainability aligns with ECBC 2017 Daylighting requirements, emphasizing achieving illuminance levels between 100 Lux and 2000 Lux for a specified percentage of floor area and time. LEED provides three options for daylight evaluation, involving simulation or measurement approaches, with a requirement for glare-control devices in all occupied spaces. Option 1 evaluates daylight using spatial daylight autonomy (sDA300/50%) and annual sunlight exposure (ASE1000,250). Option 2 involves simulation-based illuminance calculations at specific times, while Option 3 employs a measurement-based approach.

Table 5: Comparison of quality outdoor views criteria across GBRS

GBRS	Quality outdoor views - Criteria	Maximum Points / Credit
IGBC	Unobstructed vision glazing for occupants in at least 75% of spaces, maintaining a direct line of sight between 0.9 m and 2.1 m above the floor level. Obstructions -free view extending up to 8 meters from exterior glazing, allowing access to the sky or natural surroundings.	**1**
GRIHA	The assessment doesn’t directly consider the Quality Outdoor View aspect.	**0**
GEM sustainability	The framework does not allocate specific credits or points for the incorporation of outdoor views.	**0**
LEED	Visual Light Transmittance (VLT) should surpass 40%, and for 75% of the used floor spaces, an unimpeded view for 7.5 meters from the exterior glazing providing access to nature or urban landmarks to be considered.	**1**

This comparison reveals the diversity in daylighting assessment methodologies among the frameworks, with variations in criteria, simulation approaches, and measurement options. The assessment of incorporation of quality outdoor views within green building rating systems, reveals strategies are evident among the selected frameworks. Table 5 Presents comparison of quality outdoor views criteria across GBRS. Within the Indian Green Building Council (IGBC) framework, a singular point is designated for Outdoor View. The criterion outlines specific requirements, including an unobstructed line of sight to vision glazing at a designated height for occupants in the majority of regularly used spaces.This directive encompasses a range between 0.9 meters and 2.1 meters above the finished floor level, ensuring a clear view for occupants. Moreover, a prerequisite for this point includes an obstruction-free view for 8 meters from exterior glazing, coupled with access to the sky, flora, fauna, or a combination of these natural elements. Conversely, in the Green Rating for Integrated Habitat Assessment (GRIHA) system, the evaluation does not explicitly address the Quality Outdoor View component within the occupant comfort section, resulting in the absence of allocated points for this component. Similarly, GEM Sustainability also does not assign specific credits or points for the consideration of outdoor views.

On the other hand, the Leadership in Energy and Environmental Design (LEED) framework has Quality Views as a criterion, rewarding one point for ensuring unobstructed views for 75% of regularly occupied floor spaces. The criterion further stipulates a clear view extending 7.5 meters from exterior glazing, access to nature, urban landmarks, or art, and a Visual Light Transmittance (VLT) above 40%.

In examining the criteria related to artificial and indoor lighting across chosen green building rating systems (GBRS) frameworks, variations in their requirements is demonstrated (Table 6). The Indian Green Building Council (IGBC) does not explicitly outline any specific credits or criteria for artificial and indoor lighting within its Indoor Environmental Quality (IEQ) section, suggesting that this aspect is not considered in its evaluation framework. On the other hand, the Green Rating for Integrated Habitat Assessment (GRIHA) places a dedicated emphasis on artificial lighting by including a specific mandatory criterion for artificial lighting design. No points are assigned to this criterion, but compliance is required. The design must align with recommended space/task-specific lighting levels as per the National Building Code (NBC) 2016. Additionally, a minimum uniformity ratio of 0.4 is mandated. While GRIHA does not allocate points for this parameter, it underscores the importance of adherence to lighting standards. GEM Sustainability introduces a specific requirement related to artificial lighting by emphasizing the integration of Daylight/Occupancy sensors and timers on exterior lighting in common areas such as corridors, lift lobbies, reception, parking and to integrate it with the artificial lighting. Complying with this requirement is rewarded with two points, showcasing the framework's commitment to energy-efficient lighting solutions. In the Leadership in Energy and Environmental Design (LEED) framework, the Interior Lighting criteria is allocated two points. This criterion encompasses four strategies: Glare Control, Color Rendering, Lighting Control, and Surface Reflectivity. Points are awarded based on the fulfillment of these strategies, with one point for meeting one strategy and two points for meeting a total of three strategies. This multifaceted approach ensures a comprehensive consideration of aspects such as glare control, color rendering, and lighting control in indoor lighting design.

Table 6: Comparison of artificial and indoor lighting criteria across GBRS

GBRS	Artificial and indoor lighting Criteria	Maximum Points / Credit
IGBC	IGBC does not explicitly specify any credits or criteria for artificial and indoor lighting.	**0**
GRIHA	Design should conform to the suggested illumination levels suitable for the particular area or task, as outlined in the National Building Code (NBC) 2016. Additionally, a minimum uniformity ratio of 0.4 is obligatory.	**Mandatory**
GEM sustainability	Daylight and occupancy sensors, along with timers, for exterior lighting, common areas and integrate the sensors with artificial lighting systems	**2**
LEED ***1 point for single strategy and 2 points for meeting a total of 3 strategies***	1. Glare Management: Ensure Unified Glare Rating (UGR) below 19 or opt for light fixtures with luminance levels less than 7000 cd/m2.	**2**
	2. Color Rendering Index: Maintain a minimum of 90 and adhere to the Color Fidelity Index specified in IES TM-30.	
	3. Illumination Control: Implement dimmable or multilevel lighting systems for 90% of usable spaces.	
	4. Surface Reflectance: For 90% of indoors, utilize interior finishes with surface reflectance equal to or exceeding 80% for ceilings and 55% for walls.	

In summary, the comparison reveals that while IGBC and GRIHA address artificial and indoor lighting in different capacities without specific points, GEM Sustainability and LEED provide more explicit requirements and incentives for incorporating energy-efficient and effective artificial lighting solutions.

The analysis revealed distinct quantitative metrics for visual comfort within the selected green building rating systems. IGBC and LEED emphasizes parameters such as illuminance, Daylight Factor, and Spatial Daylight Autonomy (IGBC, 2018). In contrast, GEM sustainability places a stronger emphasis on Useful Daylight Illuminance, while Griha integrates a combination of Useful Daylight Illuminance and daylight autonomy (DA). Qualitative aspect were found to be explicitly addressed in Griha (uniformity ratio) and LEED (Unified Glare Rating - UGR) documentation, while IGBC and GEM sustainablilty primarily focuses on quantitative metrics.

Reconsidering the threshold limits of various daylight and glare indices becomes imperative, considering occupants' higher adaptive abilities influenced by climate, location, and culture. Research endeavors have been initiated to establish the efficacy of diverse metrics and identify the most reliable metric for daylight and glare assessment. An study focused on four metrics (UDI, sDA, sDGP, and ASE) in relation to user responses demonstrated their compatibility. This study revealed that, for daylighting, UDI exhibited a higher correlation with occupants' perception compared to sDA (89.4% vs. 73.4%). Regarding glare indices, the correlation between sDGP and occupants' glare perception surpassed that of ASE (84.2% vs. 71.1%) (Zomorodian & Tahsildoost, 2019). Similarly, among all glare indices, DGP emerged as the most suitable, displaying a strong correlation with occupants' responses and incorporating vertical eye illuminance and occupants' dissatisfaction (Carlucci et al., 2015).

5. Conclusions

The comprehensive examination of visual comfort criteria across prominent Indian green rating schemes, namely IGBC, GRIHA, GEM sustainability and LEED, has provided valuable insights into the diverse approaches taken by these systems. The findings underscore that the the comparative analysis of various green rating framework reveals a diverse landscape of evaluation criteria, scoring mechanisms, certification levels, and referenced standards. Each rating system, be it IGBC, GRIHA, GEM Sustainability, or LEED, brings its unique approach to assessing and certifying green buildings.

The quantitative metrics, such as illuminance levels, Daylight Factor, Spatial Daylight Autonomy, and Useful Daylight Illuminance, demonstrate notable variations among various rating systems. Each system typically adheres to one or two of these metrics, leading to significant differences. For instance, IGBC relies on Daylight illuminance, GRIHA opts Daylight Autonomy or UDI, GEM Sustainability incorporates UDI metrics, and LEED utilizes (sDA300/50%) and annual sunlight exposure (ASE1000,250) or daylight illuminance. This underscores the importance of tailoring each system's criteria to ensure optimal design outcomes, emphasizing the need for flexibility and adaptability in the evaluation of green building metrics. Qualitative aspects, such as glare control and lighting distribution, were found to be more explicitly addressed in Griha and LEED documentation, highlighting the importance of considering not only quantitative metrics but also the subjective experiences of occupants.

The intra-system comparisons revealed that even within a single rating system, there exist subtle variations in visual comfort criteria, suggesting the influence of specific contextual considerations and interpretations. The analysis demonstrated significant differences among the rating systems, indicating that practitioners should carefully navigate the distinctions when selecting a particular system for building certification. These findings hold practical implications for architects, designers, and policymakers involved in the sustainable building design process. Awareness of the variations in visual comfort criteria is crucial for aligning design strategies with the specific requirements of each rating system. This study fills a significant research gap by offering a detailed comparison of visual comfort criteria within Indian green building rating systems. It provides a foundation for future research endeavors, encouraging a more holistic approach to sustainable building certification processes. It can be inferred that indoor visual comfort also depends on a combination of various building envelope parameters. The optimal parameters may vary based on different climate conditions, building typologies, and indoor settings. Consequently, future studies should involve different iterations to assess various fenestration designs for all orientations. This approach aims to propose accurate and validated guidelines applicable across diverse climatic zones.

In conclusion, the exploration of visual comfort criteria across green building rating systems contributes to the ongoing discourse on enhancing occupant well-being in the built environment. The insights gained from this study can inform more informed decision-making processes in sustainable building design and certification practices.

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BALCONIES AS SHADING DEVICES FOR GLAZED OUTER SURFACES OF TROPICAL APARTMENT BUILDINGS

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ABSTRACT

Tropical regions often experience intense sunlight levels for an extended part of the year, leading to excessive heat and glare inside buildings when appropriate shading devices are absent. Glazed outer surfaces give buildings a sleek appearance; however, they often result in an uncomfortable indoor environment. In the context of Dhaka, a considerable shading depth is required for a full façade sliding glass opening, commonly utilised as a balcony door (sliding), when oriented towards the south. This study investigated the effectiveness of balconies in mitigating glare and improving the interior luminous environment. The research aims to determine the balcony design parameters to maximise daylighting and minimise glare. A detailed computational 3D model of a case tropical apartment building was developed using simulation software. Analysing factors assessed the daylighting performance of different balcony configurations. The balcony with a 915mm railing height, with a drop ended at 2150mm from the finished floor level, was found to be the best among the studied configurations. Based on the findings of simulation studies, sliding glass openings with a light shelf outer depth equal to the balcony depth and an internal depth of 500mm performed better compared to only punched or sliding doors on the adjacent wall to the balcony. Balconies that are placed one above another on each floor outperform those when balconies are placed in a zig-zag pattern on the building elevation. The balcony depth of 1370mm, the silver glossy tiles flooring (reflectance 90) and the blue colour (reflectance 20) indoor walls were found to be the best among the studied options. Finally, with these options, the recessed balcony outperforms the semi-recessed and cantilever types. The study emphasises that balconies linked to the bedrooms through glass sliding doors can effectively serve as shading devices for glazed outer surfaces of tropical buildings, reducing glare and improving daylighting.

Keywords: Balconies; Shading devices; Glare reduction; Daylighting; Tropical apartment buildings.

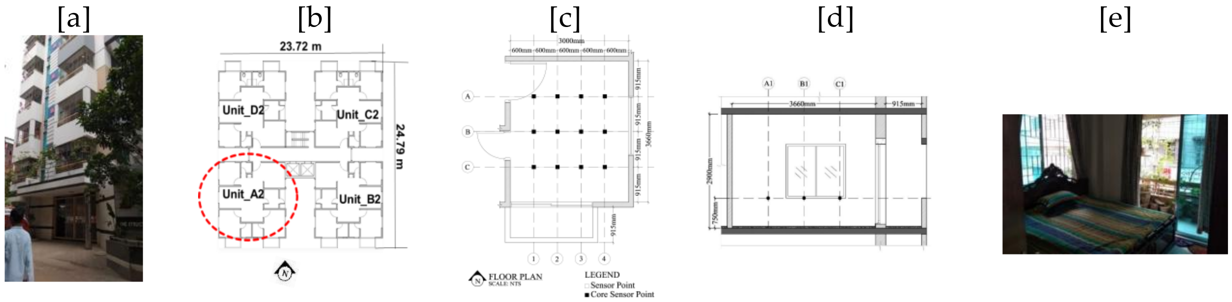
1. Introduction

Daylight is one of the primary components of a healthy atmosphere; however, in tropical countries, summer heat associated with daylight is often uncomfortable. Adding a balcony could work as a filtering space for entering daylight and purifying the air. Heating and cooling loads can be reduced inside rooms by integrating a balcony (Angeraini, 2016). Several investigations were done to find out the advantages of balcony space, conjugate execution of balcony, opening form, diversity, and internal division (Prianto and Depecker, 2003). The reduction of exterior noise and its effect on the balcony were investigated (Kim and Kim, 2007; Lee et al., 2007). Ribeiro (2020) has also done a review on balcony types available till 2020 and evaluated acoustic comfort, air quality, thermal comfort, and visual comfort; however, studies on the balcony space effect on indoor daylighting of apartments are rare. Under tropical weather conditions, such as in Dhaka, the appropriate placement of a balcony beside a room could work as shade against excessive daylight and protect the room from excessive heat. The balcony is also a connecting point between indoor and outdoor, hence connecting individuals with the surrounding neighbourhoods. By changing the balcony features, the lighting performance of indoor spaces could be enhanced. This research proposes some design parameters of balconies for enhancing indoor daylighting conditions and comfort by examining various balcony elements (i.e., ceiling, drop, partition, railing, wall and floor) on a chosen south-facing balcony next to a bedroom (Fig. 1 and Fig. 2). The study aims to find sustainable passive solutions that could assist occupants in achieving a comfortable interior environment. The goal is to provide architects and designers with practical guidelines for creating buildings that promote occupant well-being and sustainability through passive design principles.

2. Case building for base case modelling

A nine-story apartment building at Nakhalpara, Tejgaon, Dhaka, was selected as the case building (Fig. 1 [a]). The building was mostly square in shape, with four units with typical floor plans (Fig. 1 [b]). The case unit (Apartment Unit A2) was located on the 1st floor at the south-west corner of the building (a south-facing apartment). The bedroom located at the south-east corner of Apartment Unit 2, with an attached balcony adjacent to the bedroom, was selected for examination and simulation study (Fig. 1 [c]). The floor area ratio of the balcony to the bedroom was estimated to be around 4:1. The building had a 6m wide front road, creating opportunities for daylight exposure through balconies and facades (Fig. 1 [a]). Fig. 1 shows the plans, section, and images of the case building and bedroom.

Figure 1: [a] Front view; [b] Unit plan; [c] Bedroom floor plan with location of the sensor points; [d] Bedroom section showing heights of the sensor points; and [e] indoor image of the bedroom with balcony of the case building.


[a] [b] [c] [d] [e]

3. METHODOLOGY

A detailed computational 3D model of the selected apartment building was developed using simulation software. Daylight and glare simulation was performed for the virtual room with the attached balcony based on information collected from the field survey (Table 1). For simulation purposes, the entire case bedroom floor was gridded with 12 intersecting sensor points. Fig. 1 [c] shows the core and test sensor points. Three core sensor points are 2A, 2B and 2C. The sensors are placed at a height of 750mm from the finished floor level (Fig. 1 [d]), which represents the work plane height (BNBC, 2020). The amount of daylight incident on the generated grid points on the work plane was calculated.

Figure 2: Variables of balcony design.

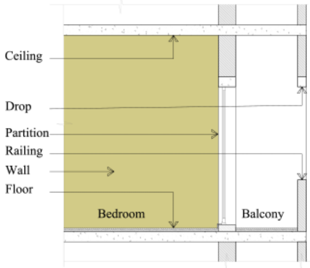
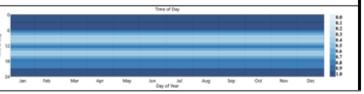


Table 1: Building and occupancy information for the simulation model.

SURVEYED ITEMS	INFORMATION
Building height	27432 mm (90')
Bedroom size	(3048 x3 658) mm
Bedroom clear height	2900 mm (9'6")
Balcony size	(915x 2100) mm
Balcony type	Cantilever
Apertures connected to the outdoor	2 (One window and one sliding door to the balcony)
Doors in Bedroom	2
Annual occupancy schedule of the case residential unit	

After identifying the design variables (Fig. 2), building information (Table 1) and simulation parameters (Table 2) for the selected case space, the daylighting analysis was conducted with the following material properties identified from the field survey.

- **Wall:** 115mm thick brick with a 10mm plaster finish on both sides; 2.620 U Value; 0.418 solar absorption; decrement in temperature: 0.7 and a diffuse reflection of 70%.
- **Window:** a single pane of glass with an aluminium (a diffuse reflection of 50%) frame is used (no thermal break); 6.0 U value; 0.94 solar absorptions; decrement in temperature: 1.74 (refractive index of glass).
- **Floor:** 100mm thick concrete slab; 0.88 is the U value; 0.467 solar absorption; decrement in temperature: 0.3, and a diffuse reflection of 50%.
- **Shading device:** 0.896 is the U value; 0.9 solar absorption; a decrement in temperature: 0.58, and a diffuse reflection of 40%.
- **Roof:** concrete with a plaster finish and a diffuse reflection of 40%.

For dynamic performance measures, various sorts of overall rating systems were utilised in the past. Reinhart (2006) employed a method for daylight performance evaluation in which key sensor points were centred on a central axis. The performance measures' average values are then shown in a table (e.g., Table 3), and rating points are allocated based on their performance. Because three separate parameters are investigated in this study (e.g., DA, DAmax, and UDI), a wide range of parametric settings for each step was investigated. Different rating points were assigned at different levels. The highest point (for example, 7 points) denoted the best performance among the choices analysed, while the lowest point (for example, 1 point) showed the worst performance. The ultimate score was calculated by adding the scores of each performance metric.

The weather file of Dhaka (BGD_Dhaka.419230_SWERA.epw) was downloaded from the EnergyPlus website (energyplus.net/weather) and inserted in the climate data section of DAYSIM. The daylighting performance of different balcony configurations was assessed by analysing factors such as Daylight Autonomy (DA), Maximum Daylight Autonomy (DAmax) and Useful Daylight Index (UDI$_{<100}$, UDI$_{100-200}$ and UDI$_{>2000}$). The sum of the points for each parameter generated the overall score. To generate realistic lighting levels, these models were then exported to RADIANCE synthetic imaging software and finally analysed with the DAYSIM simulation program for annual performance evaluation.

4. Simulation and results

In this research, the initial simulation model was developed using the ECOTECT V5.0 tool. Balcony configurations and locations were examined to get the best result of glare-free daylight in bedrooms beside the balconies. The window of the bedroom was left open without any blinds. The experiment was done in eight different phases (Fig. 3), and the phases progressed while keeping previous findings constant. Considering the core work plane sensor approach, the summary results of annual dynamic simulations are described in this section.

Figure 3: Balcony performance evaluation sequence.

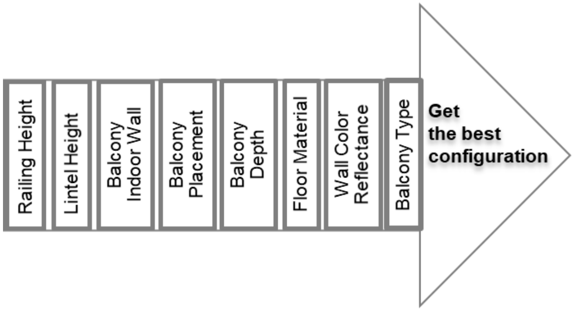


Table 2: Building information for the simulation model.

PARAMETERS	SPECIFICATIONS
Location	Dhaka
Longitude	90.40° E
Latitude	23.80° N
Local Terrain	Urban
Precision	High
Time zone, Time Frame	+6 GMT; Whole year
Simulation Time	6.00 to 18.00
Sky Illumination Model	Perez, all possible sky models round the year
Unit of dimension	SI metric (m, cm, mm) Photometric dimension: SI (Lux, cd/m2)
The window glazing portion's light qualities	90% transmission; Pollution factor: 0.70; Framing factor: 0.90; Maintenance factor: 0.85

4.1 Balcony railing height

The seven balcony railing heights studied are coded according to height level as BR1050, BR900, BR750, BR600, BR450, BR300 and BR150, where BR1050 represents a railing height of 1050mm from the finished floor level, and so on (Fig. 4). Table 3 shows a summary of the annual climate-based daylight modelling (CBDM) simulation output with rating points and a ranking of the seven types of railing height configurations for balconies studied. Considering the rating points, BR1050 and BR900 scored the highest and ensured a uniform distribution of daylight compared to other types of balcony railing heights; however, according to the floor area ratio (FAR) rules, railing height should be 800-900mm and for a special reason, an extra rail could be added (BNBC 2020). Therefore, the BL900 was fixed as the working railing height. Fig. 4 shows the studied balcony railing heights, contour band and false colour maps, and DA and $UDI_{100\text{-}2000}$ distributions of BR 900.

Figure 4: Studied balcony railing height configurations [left], contour bands [top-right] and false colour [right-middle] maps, and DA [bottom-middle] and $UDI_{100\text{-}2000}$ [bottom-right] distributions of BR 900.

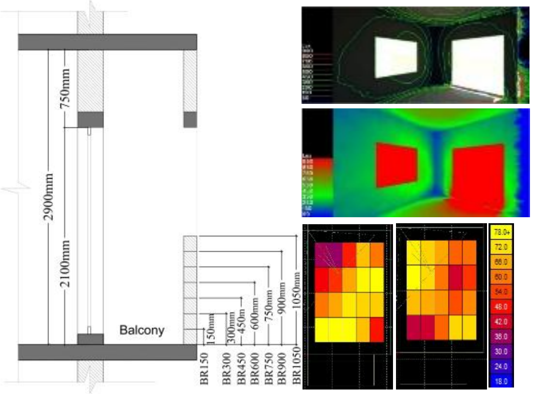


Table 3: Annual CBDM simulation outputs with rating points (RP) and ranking of balcony railing depths.

Railing Height (mm)	Value and RP	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100\text{-}2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
BR1050	Value	70.33	3.33	24.33	66.33	9.33	29	1
	RP	3	7	5	7	7		
BR900	Value	70.67	3.33	24	66	10	29	1
	RP	4	7	6	6	6		
BR750	Value	70.67	4	24	65	10.67	25	3
	RP	4	6	6	4	5		
BR600	Value	71	4.33	24	65.33	10.67	26	2
	RP	5	5	6	5	5		
BR450	Value	71.33	4	24	64.67	11.67	25	3
	RP	6	6	6	3	4		
BR300	Value	71.67	4.33	23.67	64.33	12	24	4
	RP	7	5	7	2	3		
BR150	Value	71.33	4.67	23.67	64	12.33	20	5
	RP	6	4	7	1	2		

4.2 Balcony drop level

After finding the best balcony railing height, balcony drops ended at six different levels from the finished floor level were analysed (Fig. 5). The six balcony drop levels were coded according to height level as BL2150, BL2300, BL2450, BL2600, BL2750 and BL2900, where BL2150 represents a balcony drop that ends at 2150 mm from the finished floor level, and so on. Table 4 shows the annual CBDM simulation outputs with rating points and ranking of the studied balcony lintel height configurations. Considering the rating points, BL2150 scored the best among the other types of balconies and ensured a uniform distribution of daylight (Fig. 5).

Figure 5: Studied balcony lintel height configurations [left], contour band [right-top] and false colour [right-middle] maps; and DA [bottom-middle] and UDI [bottom-right] distributions of BL2150.

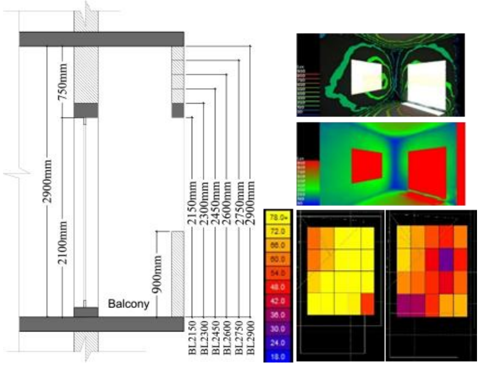


Table 4: Annual CBDM simulation outputs with rating points (RP) and ranking of different balcony drop bottom heights.

Drop bottom end Height (mm)	Value and RP	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100-2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
BL2150	Value	70.67	3.33	24	66	10	23	1
	RP	3	6	2	6	6		
BL2300	Value	72.33	5.67	23.67	61.67	14.67	22	2
	RP	4	5	3	5	5		
BL2450	Value	72.33	7	23.33	58.67	18	20	3
	RP	4	4	4	4	4		
BL2600	Value	73	8.33	23	55.33	21.67	19	4
	RP	5	3	5	3	3		
BL2750	Value	73.33	10	22.67	53.67	23.67	18	5
	RP	6	2	6	2	2		
BL2900	Value	73.33	11.33	22.67	51.67	25.67	15	6
	RP	6	1	6	1	1		

4.3 Adjacent wall to bedroom

Three configurations of partition walls were investigated (Fig. 6): sliding with glass (SG); 500 mm deep light shelf in both the interior and exterior of the bedroom (LS); and 500 mm deep light shelf in interior and exterior light shelf depth equal to balcony floor depth (FC). Table 5 shows a summary of the annual CBDM simulation outputs with rating points and ranking. Considering the points, FC scores the best. Fig. 6 shows the studied balcony adjacent wall configurations, contour band and false colour maps, and DA and $UDI_{100-2000}$ distributions for the best output (FC).

Figure 6: Studied balcony adjacent wall configurations [top], contour band [left-middle] and FC false colour [left-bottom] maps; and DA [bottom-middle], UDI [bottom-right] distributions of FC.

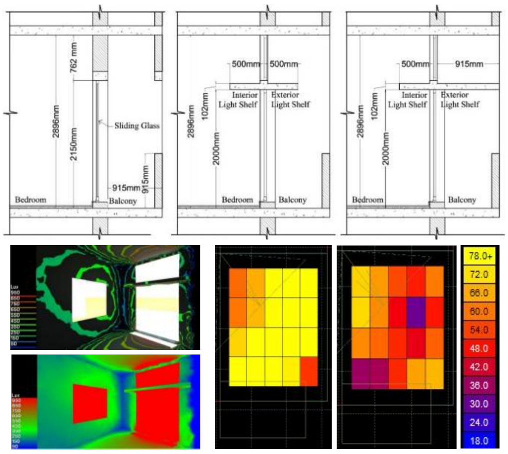


Table 5: Annual CBDM simulation outputs with rating points (RP) and ranking of studied balcony adjacent wall configurations.

Balcony Wall	Value and RP	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100-2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
SG	Value	70.67	3.33	24	66	10	11	2
	RP	1	2	2	3	3		
LS	Value	72.67	6.67	23.33	59.67	16.67	11	2
	RP	3	1	3	2	2		
FC	Value	71.33	3	24	66	10	13	1
	RP	2	3	2	3	3		

4.4 Balcony placement on building elevation

Two balcony placements were compared: one had balconies in the same place for all floors coded as BA, and the other had balconies on alternative floors in the same place with zig-zag placement in terms of elevation coded as BZ (Fig. 7). Table 6 shows a summary of annual CBDM simulation results and ranking points. Considering the rating points, BA scored the highest and ensured a uniform distribution of daylight. Fig. 7 shows contour band and false colour maps, human sensitivity distributions, DA and UDI$_{100\text{-}2000}$ for the best output, i.e., BA.

Figure 7: Studied balcony placements on building elevation [top-left]; DA [top-middle] and UDI [top-right] distributions; and contour band [bottom-left], false colour [bottom-middle], human sensitivity [bottom-right] maps of BA placement.

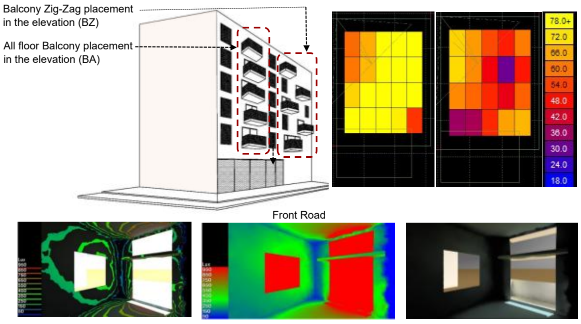


Table 6: Annual CBDM simulation outputs with rating points (RP) and ranking of balcony placements

Balcony Placement	Value and RP	DA (%)	DA max (%)	UDI$_{<100}$ (%)	UDI $_{100\text{-}2000}$ (%)	UDI$_{>2000}$ (%)	Total RP	Ranks
BA	Value	71.33	3	24	66	10	8	1
	RP	1	2	1	2	2		
BZ	Value	73.33	5	23.33	55	21.67	7	2
	RP	2	1	2	1	1		

4.5 Balcony floor depth

Five different balcony floor depths were analysed, keeping the previous outputs fixed (Fig. 8). The five balcony floor depths studied were coded as BD915, BD1065, BD1220, BD1370, and BD1525, where BD915 represents a balcony depth of 915mm and so on. Table 7 shows a summary of annual CBDM simulation results and rating points with the ranking. Considering the rating points, the BD1370 scored the highest among the studied depths and ensured a uniform distribution of daylight. Fig. 8 shows contour band and false colour maps, and DA and UDI$_{100\text{-}2000}$ distributions of the best output (BD1370).

Figure 8: Studied balcony floor depth configurations [left], contour band [top-right] and false colour [middle-right] maps; and DA [bottom-middle] and UDI [bottom-right] distributions of BD1370.

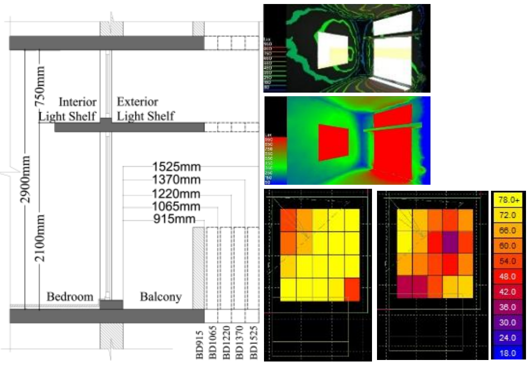


Table 7: Annual CBDM simulation outputs with rating points (RP) and ranking of balcony floor depths

Floor Depth (mm)	Value and RP	DA (%)	DA max (%)	UDI$_{<100}$ (%)	UDI $_{100\text{-}2000}$ (%)	UDI$_{>2000}$ (%)	Total RP	Ranks
BD915	Value	71.33	3	24	66	10	10	5
	RP	2	3	3	1	1		
BD1065	Value	82.33	2.33	13.67	76.67	9.33	18	4
	RP	5	4	5	2	2		
BD1220	Value	80	1.67	14.33	79.33	6.67	20	2
	RP	3	5	4	4	4		
BD1370	Value	80	1.67	14.33	79.67	6	22	1
	RP	3	5	4	5	5		
BD1525	Value	80.33	1.67	14.33	77.67	8	19	3
	RP	4	5	4	3	3		

4.6 Balcony floor material

Five types of materials with varying reflectance (ET, 2012) were considered for evaluation as floor materials for bedrooms and balconies (Fig. 9), i.e., mat tiles (MT; reflectance 20), concrete or NCF flooring (CO; reflectance 40), timber flooring (TF; reflectance 60), epoxy flooring (EF; reflectance 80), and silver glossy tiles (highly polished) flooring (GT; reflectance 90). Table 8 shows a summary of annual CBDM simulation results and ranking points of different studied balcony floor materials.

Considering the rating points, GT90 scored the highest and ensured a uniform distribution of daylight. Fig. 9 shows contour band and false colour maps, and DA and $UDI_{100-2000}$ distributions of the best output (GT90).

Figure 9: Studied balcony floor materials [left]; contour band [top-right] and false colour [middle-right] maps; and DA [bottom-middle] and UDI [bottom-right] distributions of GT90.

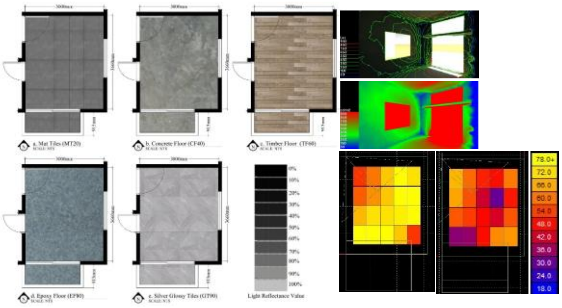


Table 8: Annual CBDM simulation outputs with rating points (RP) and ranking of wall colors

Floor Material	Value and RP	DA (%)	DA max (%)	$UDI_{<100}$ (%)	UDI 100-2000 (%)	$UDI_{>2000}$ (%)	Total RP	**Ranks**
MT20	Value	82.33	6.33	13.33	62.67	24	13	**5**
	RP	5	1	5	1	1		
CF40	Value	81.67	2.33	14	76	10	18	**2**
	RP	3	4	3	4	4		
TF60	Value	81.67	3.67	13.67	71.33	14.67	16	**3**
	RP	3	3	4	3	3		
EF80	Value	82	5.33	13.33	66.33	20.33	15	**4**
	RP	4	2	5	2	2		
GT90	Value	80.67	1.67	14	79	7	20	1
	RP	2	5	3	5	5		

4.7 Balcony wall colour

The six-wall colours (Fig. 10), i.e., white (RW; reflectance 85), yellow (RY; reflectance 68), green (RG; reflectance 30), blue (RB; reflectance 20), red (RR; reflectance 18), and black (RK; reflectance 07) were studied as the internal wall colours for bedrooms and balconies. White was considered an external building wall colour. Table 9 shows annual CBDM simulation outputs with rating points and ranking of different studied balcony wall colours. Considering the rating, RB scores the highest. Fig. 10 shows contour band and false colour maps, and DA and $UDI_{100-2000}$ distributions of the best output (RB).

Figure 10: Studied balcony and bedroom wall colour [left]; contour band [top-right] and false colour [middle-right] maps; and DA [bottom-middle] and $UDI_{100-2000}$ [bottom-right] distributions of RB

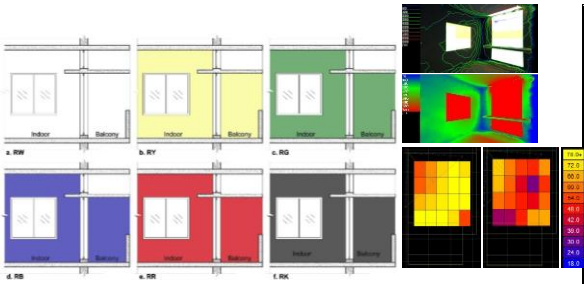


Table 9: Annual CBDM simulation outputs with rating points (RP) and ranking of balcony types

Wall Color Reflectance	Value and RP	DA (%)	DA max (%)	$UDI_{<100}$ (%)	UDI 100-2000 (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
RW	Value	83.67	8.33	12.67	56	31	20	4
	RP	6	3	6	3	2		
RY	Value	82	4.67	13.33	69.33	17.33	22	3
	RP	5	4	5	4	4		
RG	Value	80	2.33	14.33	77.33	8.67	22	3
	RP	3	5	4	5	5		
RB	Value	80.33	2	14.33	77.67	8.33	26	1
	RP	4	6	4	6	6		
RR	Value	80	2	14.33	77.67	8.33	25	2
	RP	3	6	4	6	6		
RK	Value	83.67	8.33	12.67	55.33	32	20	4
	RP	6	3	6	2	3		

4.8 Balcony types

Three popular local types of balcony configurations, i.e., recessed, semi-recessed and cantilever, were coded as R, SR, and C. Fig. 11 shows the plan of the studied local balcony types. Table 10 shows a summary of annual CBDM simulation results for the three studied types of balcony configurations and performance evaluation rating points with ranking. Considering the rating points, type R scored the highest and ensured a uniform daylighting distribution. Fig. 11 shows contour band and false colour maps, and DA and $UDI_{100-2000}$ distributions of the best output (type R).

Figure 11: Studied balcony types [top]; contour band

[middle-left] and false colour [bottom-left] maps; and DA [bottom-middle] and UDI$_{100\text{-}2000}$ [bottom-left] distribution of R.

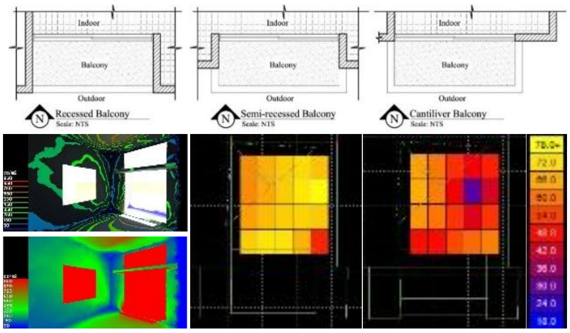


Table 10: Annual CBDM simulation outputs with rating points (RP) and ranking of different studied balcony types.

Balcony Type	Value and RP	DA (%)	DA max (%)	UDI$_{<100}$ (%)	UDI $_{100\text{-}2000}$ (%)	UDI$_{>2000}$ (%)	Total RP	Ranks
R	Value	75.67	0	14.67	82.67	2.67	12	1
	RP	1	3	2	3	3		
SR	Value	78.33	0	14.67	79.67	6.33	11	2
	RP	2	3	2	2	2		
C	Value	80.33	2	14.33	77.67	8.33	10	3
	RP	3	2	3	1	1		

5. Summary

The configuration with a railing height of 915 mm and a drop terminating at 2150 mm above the finished floor level proved to be the most effective among those examined. Simulation results indicated that sliding glass openings combined with a light shelf, having an external projection equal to the balcony depth and an internal extension of 500 mm, delivered superior performance compared to simple punched or sliding doors placed on the wall adjoining the balcony. Continuous balconies aligned vertically on each floor were more efficient than those arranged in a staggered, zig-zag manner along the façade. A depth of 1370 mm, paired with silver glossy floor tiles (reflectance 90) and blue interior walls (reflectance 20), emerged as the most favorable combination. Under these conditions, recessed balconies demonstrated better performance than both semi-recessed and cantilevered alternatives. Fig. 12 shows a perspective view of the recessed balcony with the best features included in the study. Table 11 presents the summary of the findings with the best output values among the studied balcony parameters.

Figure 12: Perspective view of recessed balcony with the best features included

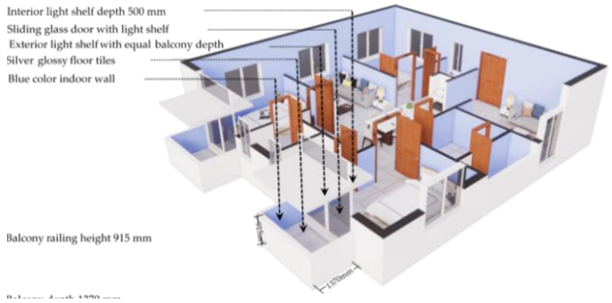


Table 11: Best outputs among the studied balcony parameters

No.	Type of Analysis	Best Output	Code
1	Balcony railing height	900mm	BR 900
2	Balcony drop end level	2150mm	BL 2150
3	Balcony adjacent wall	Sliding glass opening with light shelf (indoor 500mm depth and outdoor as balcony depth)	FC
4	Balcony placement	Balconies in the same place for all floors	BA
5	Balcony floor depth	1370 mm	BD 1370
6	Balcony floor material	Silver glossy floor tiles, LRV90	GT
7	Balcony wall color	Blue color, reflectance 20	RB
8	Balcony type	Recessed balcony	R

6. Conclusion

In the context of Dhaka, an appropriate shading depth for a full façade sliding glass aperture (usually used as a door to the balcony) for south orientation is huge. A balcony, attached to the bedroom with a glass sliding door, can be treated as a shading device to ensure glare-free daylighting inside the bedroom. The balcony with the recommended parameters in this research will redirect and transmit daylight in the interior space and will provide uniform illumination distribution in bedrooms. Apart from improving the luminous environment, daylight inclusion is also related to aesthetics, economies, sound transmission, ventilation, safety, security and subjective concerns of privacy and view. Due to time restrictions and resource constraints, daylight inclusion on the mentioned concerns was beyond the scope of this research; however, it can form the basis of further research.

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PASSIVE DESIGN FOR LIGHT AND LEARNING: INTEGRATING SUSTAINABLE FORM AND FAÇADE IN ARCHITECTURAL EDUCATION SPACES FOR HIGHER BUILDING RATING

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ABSTRACT

Educational buildings in high-density tropical cities such as Dhaka often suffer from poor daylight access, leading to excessive energy use and diminished occupant comfort. This research aims to develop a sustainable, low-energy design strategy for enhancing daylighting in architectural education spaces through climate-responsive modifications to building form and façade design. Using a case study of an existing university building in Dhaka, the study explores how spatial reconfiguration and an adaptive, photovoltaic-integrated ethylene tetrafluoroethylene (ETFE) envelope can improve daylight performance while accommodating structural constraints and evolving functional needs. Climate-based daylight simulations were conducted using ClimateStudio in Rhinoceros 3D and Grasshopper. Results reveal a substantial enhancement in daylight quality: average illuminance increased from 410 lux to 921 lux, spatial daylight autonomy ($sDA_{300/50\%}$) improved from 46% to 76.3%, and annual sunlight exposure ($ASE_{1000,250h}$) remained within acceptable LEED thresholds at 8.6%. These advancements enabled the design to achieve the maximum 3 daylighting credits under LEED, reflecting superior visual comfort, passive energy savings, and design efficiency. The study presents a replicable model for net-zero-ready retrofits in institutional buildings, reinforcing the value of passive daylighting strategies in attaining higher green building ratings in resource-constrained urban environments.

Keywords: Building Simulation; Climate-responsive; Daylighting; Energy Efficiency; Educational Space.

1. Introduction

In tropical cities facing rapid urbanization, such as Dhaka, educational facilities face ongoing pressures from land scarcity, high energy demand, and poor indoor environmental quality. In this context, daylighting emerges as a prime priority both environmentally and educationally. Daylight provides visual comfort, strengthens links to the natural environment, and improves student health and mental well-being. Research shows that classrooms with daylighting produce better learning outcomes, greater mood, and enhanced cognitive performance (Gelfand & Freed, 2010; Renner, 2022) compared to classrooms without daylighting. Manning (1967) also noted that daylight helps to reduce eye strain and regulate circadian rhythms, which promotes concentration and academic performance. From an energy perspective, lighting represents between 25-40% of total electricity across the electricity use of multi-storey educational buildings, and some educational institutions expend more than 40% of their consumption on lighting (Alrubaih et al.,2013; Mahlia et al., 2011). Using appropriate façade orientation, glazing design, and shading, it is possible to significantly reduce this energy load: reports claim reductions up to 76% in tropical schools (Tanachaikhan, 2015). Passive retrofit approaches such as shading devices and upgraded glazing have fully demonstrated improvement in daylight autonomy and reduction in glare, and energy demand, even in resource-limited contexts (Chung-Camargo et al., 2024).

Tropical climates also have a number of glare and overheating challenges. Dhaka's hot-humid conditions, amplified by elevating maximum temperatures and seemingly unending humidity (Chakraborty, 2019), increasingly put classrooms at risk for thermal discomfort. Studies conducted in Sri Lanka showed that although classrooms with daylight are often positively correlated with comfort, classrooms with poor lighting design will have some excessive glare and resort to using artificial lights, thereby compromising learning outcomes (Wijesundara & Gamage, 2021). Shading technologies can be great solutions in such contexts. Rubel and Joarder (2024) highlighted that upon optimizing both egg-crate and brise-soleil shading in Dhaka, they were able to demonstrate reductions in glare, improvements to daylight quality, as well as reductions in cooling loads. Şendur (2023) also led findings in Turkish schools to show that glazing ratio, orientation, and angle of obstructions significantly affect daylight sufficiency and glare risk.

Innovative materials and computational design tools are expanding horizons in addition to standard devices. Pavlović et al. (2018) discuss ethylene-tetrafluoroethylene (ETFE), a lightweight and highly transparent substitute for glass with less embodied energy and high daylight allowance, allowing designers to manipulate light quality, heat gain, and environmental outcomes. ETFE's flexibility allows designers to navigate daylighting parameters and considerations together. Additionally, Iqbal et al. (2023) argue that, in warm-humid climates, comfort cannot depend on mechanical cooling or the use of electric-powered comfort devices. Passive techniques that depend on the behavioural and physiological adaptation of inhabitants are essential.

Urban-scale issues complicate daylight access. Studies of urban heat island effects have illustrated the ways in which entrenching urbanity and uncovering developing vegetation are central to diminishing daylight access, increasing thermal load (Lee, Boubekri, & Liang, 2019). In Dhaka, staggering levels of unregulated urban growth have also aggravated the situation, eliminating opportunities for daylight within schools. Integrating reflective surfaces, vegetation, and permeability into urban planning should help decrease heat load while providing better daylight access for the buildings around them. In summary, the impact of the development of daylight-responsive design principles in institutions of education across tropical cities has the potential to be a transformative impact. Given this, optimising daylight performance is essential for energy savings and supporting sustainable, healthy environments. This study examined how the building's form and façade can be redesigned to enhance daylighting and visual comfort, thereby contributing to improved energy efficiency and occupant well-being, leading to the achievement of higher building ratings.

2. Methodology

The research began with a background study, including a literature review on climate-responsive design, daylight optimisation, and sustainable building strategies. This was followed by a context study and data collection, where the case building's existing functional and environmental challenges were identified. The weather file for Dhaka in .epw format was downloaded from the EnergyPlus website and inserted in the climate data section of the ClimateStudio plugin within Rhinoceros 3D software to generate the simulations using the LEED 4.1 format. An alternative design was developed, focusing on rethinking the spatial configuration to enhance daylight penetration, improve daylight quality, and optimise functionality as an educational building. A climate-responsive facade with ETFE was integrated as an innovative and sustainable module to maximise daylight efficiency.

Figure 1: Major phases of the research framework.

The metrics used within the case building and its alternative design proposal to evaluate the daylighting conditions are as follows (Chaloeytoy et al., 2020; Lee et al., 2019; USGBC, n.d.).

- Mean illuminance: The average illuminance over the regularly occupied floor area over occupied hours.
- Spatial daylight autonomy (sDA$_{300/50\%}$): This matrix illustrates the percentage of floor area with 300 lux for at least 50% of the occupancy hours. The simulations attempt to model different sky conditions based on climate to determine how much daylight indoor spaces receive over the year, compared to the available illumination.
- Annual sunlight exposure (ASE$_{1000,250h}$): This matrix describes the proportion of floor area that receives direct sunlight greater than 1000 lux for over 250 hours while highlighting over-illuminated portions.
- Daylight glare probability (DGP): Annual glare in ClimateStudio is assessed using the DGP metric, which predicts discomfort glare likelihood based on a 180° fisheye view, categorised into four levels ranging from imperceptible to intolerable glare (e.g., $0.38 \leq DGP \leq 0.45$ range is considered 'disturbing glare', and $DGP \geq 0.45$ or 45% is considered 'Intolerable Glare').

In the performance comparison stage, the alternative design was evaluated against the existing case building through simulations and performance metrics such as average illuminance, sDA$_{300/50}$%, ASE$_{1000,250h}$, DGP, and Leadership in Energy and Environmental Design (LEED) credit points, to identify the effectiveness of the form and facade. Finally, the recommendation phase provided insights for future research and practical applications in the sustainable architectural design of educational institutions.

Table 1: Input parameters for daylight simulations

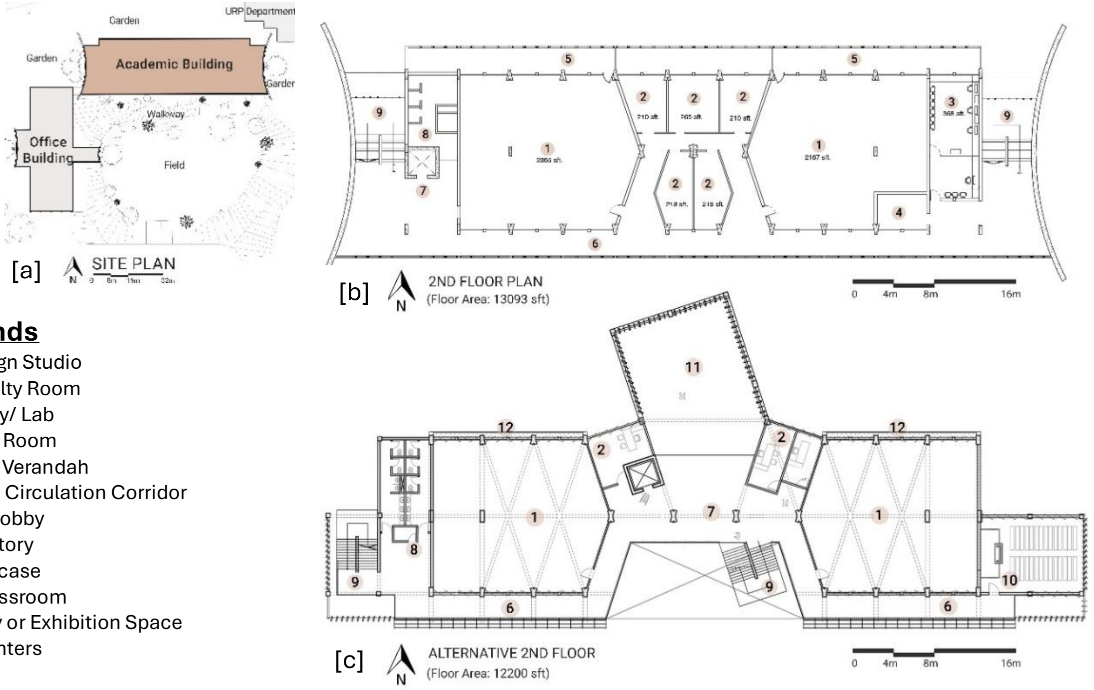
Parameter	Input Value	Reference/Source
Weather file	BGD_Dhaka.419230_SWERA.epw	EnergyPlus database
Simulation tools	ClimateStudio, Grasshopper (Rhinoceros 3D)	Study setup
Simulation grid	1 m × 1 m	ClimateStudio default
Occupancy schedule	9:00 AM – 5:00 PM (weekdays)	Field investigation
Illuminance target	500 lux (working plane)	CIBSE, IES standards
Metrics evaluated	Mean illuminance, $sDA_{300/50\%}$, $ASE_{1000,250h}$, DGP	LEED v4.1 and literature (Chaloeytoy et al., 2020; Lee et al., 2019)
Glare analysis	DGP (fisheye view, annual simulation)	Chaloeytoy et al., 2020
Sensor height	0.8 m above finished floor	LEED daylight protocol

2.1 Case Building and Its Features

The five-storey academic building of the Department of Architecture, Bangladesh University of Engineering and Technology (BUET) (coordinates 23°43’ N and 90°23’ E), located in Dhaka’s tropical savanna (Aw) climate (according to the Köppen-Geiger climate classification), was selected as the case building for the base case analysis. The academic building of the Urban and Regional Planning (URP) Department was located near the northeast corner of the case building, and the Administration building of the Department of Architecture was connected to the academic building via a corridor on both the ground and ground floors (Figure 2[a]).

The RCC-framed structure building with brick walls is elongated in the east-west direction. The 2nd floor of the case building was chosen for daylighting analysis. This floor is one of the typical floors of the case building that serves various functional spaces, including two design studios and several faculty rooms in the middle of the floor, lavatories at the west, and two staircases at the east and west ends of the building, as shown in Figure 2[b]. Along with the thick curved walls at the east and west, the staircases serve as heat-buffering elements (Rahman & Haider, 2023). Observations and interviews by the occupants suggested that the two faculty rooms on the south, between the two design studios on each floor, hinder daylight penetration in the other three faculty rooms on the north. The corridors around the north faculty rooms mostly stay dark throughout the day. The rear verandah spaces of the design studios on the north side, featuring louvres, have a similar width to the main circulation corridor on the south. Given Bangladesh's climatic context, the rear verandahs neither serve a necessary role in protecting the north façade nor are they effectively utilised.

Figure 2: [a] Site context of case building; [b] 2nd-floor plan of case building; and [c] 2nd-floor plan of the alternative design.



Legends

(1) Design Studio
(2) Faculty Room
(3) Utility/ Lab
(4) Staff Room
(5) Rear Verandah
(6) Main Circulation Corridor
(7) Lift Lobby
(8) Lavatory
(9) Staircase
(10) Classroom
(11) Jury or Exhibition Space
(12) Planters

2.2 Alternative Design of the Building and Its Features

The proposed alternative design (Figure 2[c]) addressed the issues of the case building sensitively by exploring innovative forms and spatial configurations to respond to the regional climatic conditions of the location, such as improving daylighting conditions and solar heat gain. On the second floor, the space between the studio classrooms extends northward to create a double-height exhibition area, which can also serve as a jury or exhibition space for student projects, as this specific function was absent in the existing building. In the middle, the linear characteristic of the south façade was broken with the modification of the form, as shown in Figure 2[c]. This area helps ample daylight to penetrate inside the building, and the jury space benefits from diffused northern light. The south side can be considered the heart of the building, designed for multi-layered activities, including student interactions. It has views of a picturesque field and a semi-outdoor staircase.

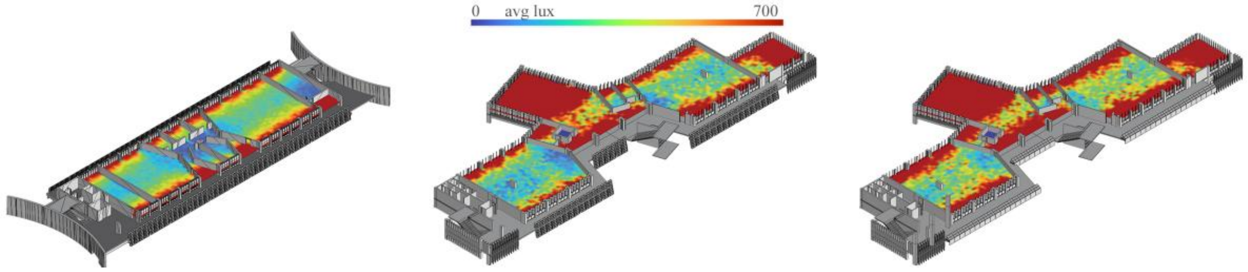
Figure 3: Alternative façade design proposal for phases 2 and 3: [a] View from the corridor showing rail-attached photovoltaics and ETFE foil panels; [b] Vertical louver panels at the west facade.

[a] [b]

3. Results

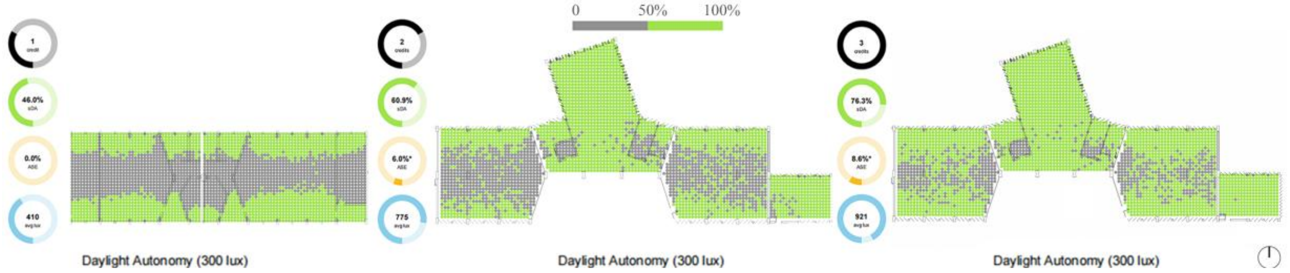
The comparison of daylight simulation results was done in three phases. Daylight simulations were conducted for the existing case building (Phase 1) and compared with the proposed alternative designs in two configurations: with the existing facade (Phase 2), and with a PV-integrated ETFE facade (Phase 3). Only long-term occupied spaces, such as the two design studios, faculty rooms, utility/lab, and classroom spaces, were considered in the daylight simulations. Lavatories, staircases, the main circulation corridor, the rear verandah, and their adjacent spaces were excluded from the analysis, as shown in Figures 4, 5, and 6. According to standards set by AS/NZS 1680.2.3 (2008) and IS 2440 (1975), the general classroom area requires an illuminance range of 240–320 lx, and reading and writing tasks need 300–500 lx, with detailed activities such as drafting needing an illuminance of 800 lx (BIS, 1975; JTC, 2008). As per the Chartered Institution of Building Services Engineers Lighting Code (CIBSE, 2022), it is advised to maintain a minimum illuminance level of 300 lux on the working plane (Wijesundara & Gamage, 2021).

Figure 4: Comparison of mean illuminance (lux) across [a] Phases 1, [b] Phase 2, and [c] Phase 3 at the 2nd-floor level.



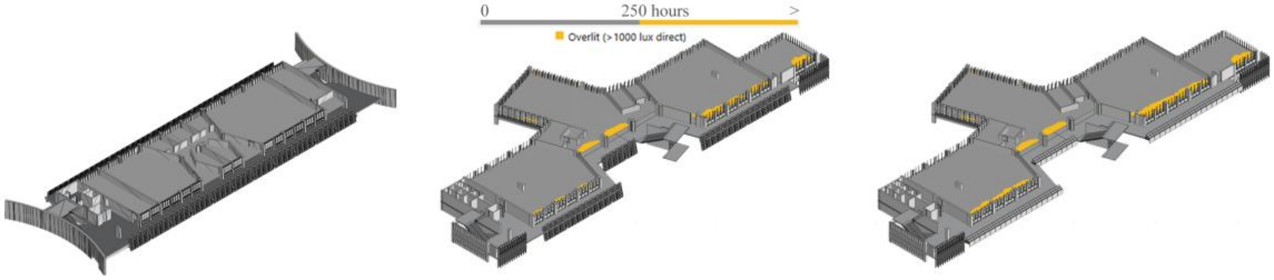
[a] [b] [c]

Figure 5: Comparison of $sDA_{300/50\%}$ across: [a] Phases 1, [b] Phase 2, and [c] Phase 3 at the 2nd-floor level.



[a] [b] [c]

Figure 6: Comparison of $ASE_{1000,250h}$ across: [a] Phases 1, [b] Phase 2, and [c] Phase 3 at the 2nd-floor level.



[a] [b] [c]

Table 2 presents a detailed comparison of daylighting performance across three design phases, highlighting both improvements in daylight and potential challenges. In Phase 1 (Base Case), the average illuminance was 410 lux, which suggested relatively low daylight penetration into the space. The $sDA_{300/50\%}$ value of 46% indicated that nearly half of the space met the target illuminance for only 50% of the day, which may result in areas relying heavily on artificial lighting. With 0% $ASE_{1000,250h}$, there were no concerns regarding glare (measured at 23.7%, which falls within the 'imperceptible glare' range) or overheating, making it a safe but less optimal design in terms of daylight utilisation. The Base Case received only 1 LEED credit, reflecting this basic level of performance.

Table 2: Comparison of daylighting performance across three phases (Source: the authors)

METRIC	PHASE 1	PHASE 2	PHASE 3
Mean illuminance (lux)	410	775	921
$sDA_{100/50\%}$ (%)	46	60.9	76.3
$ASE_{1000,250h}$ (%)	0	6	8.6
DGP (%)	23.7%	44.6%	11.3%
LEED Credit	1	2	3

The most substantial improvements occurred in Phase 3 (Alternative Design + ETFE), with the average illuminance reaching 921 lux and an impressive 76.3% of the space achieving $sDA_{300/50\%}$. This means most of the space received ample daylight, minimising the need for artificial lighting and enhancing energy efficiency. The $ASE_{1000,250h}$ value rose to 8.6%, still under the tolerable limit (i.e., less than 10%), suggesting that while the daylight performance is optimised, there is a higher likelihood of glare and overheating. The DGP is measured as low as 11.3%. The solar exposure to the double-height jury and its adjacent spaces contributes to the overall value. This phase received 3 LEED credits, reflecting its advanced daylighting performance and energy-efficient design. The addition of ETFE foil, a translucent material that allows for increased daylight, is likely responsible for the boost in illuminance. Careful design strategies, such as internal movable shading or glazing choices, will be necessary to mitigate the higher $ASE_{1000,250h}$ values.

The progression across the three design phases reveals a deliberate, performance-driven enhancement of daylighting quality, aligning closely with LEED v4 criteria for daylight credit under the Indoor Environmental Quality (IEQ) category. The significant improvement in both mean illuminance and $sDA_{100/50\%}$, while keeping $ASE_{1000,250h}$ within acceptable thresholds, was instrumental in securing the maximum of 3 LEED daylight credits in Phase 3. The results underscore a synergistic application of passive design strategies, including daylight-optimized building orientation, façade articulation, and envelope transparency, that improved performance without relying on energy-intensive systems. By leveraging parametric simulations and iterative design refinement, the project achieved quantifiable daylighting quality and visual comfort, which are essential to both occupant well-being and high-performance green building certification. This outcome illustrates how climate-responsive passive design can serve as a cost-effective, scalable strategy for educational facilities in tropical contexts to meet zero-energy goals and attain top-tier performance in building rating systems, i.e., LEED.

Overall, while the alternative designs progressively improved daylight access and energy efficiency, they also introduced challenges related to potential glare and thermal discomfort. The critical insight was that maximising daylighting requires balancing light quality with occupant comfort, as excessive sunlight exposure can lead to undesirable side effects. Further optimisation may be needed in Phase 3 to reduce glare while maintaining the benefits of increased daylight. Simulation results depend on weather data from Dhaka Tejgaon, although these data may not accurately represent the true local area weather patterns. The model excluded existing vegetation, which may have increased the glare and $ASE_{1000,250h}$ value.

4. Conclusion

This study demonstrates that strategic enhancements in building form and façade design can significantly improve daylighting performance in educational spaces, leading to measurable gains in energy efficiency and indoor environmental quality. Through iterative simulations and passive design interventions, including the integration of a PV-embedded ETFE envelope, the final design achieved a mean illuminance of 921 lux, 76.3% spatial daylight autonomy, and controlled annual sunlight exposure within LEED limits. These improvements enabled the project to secure the maximum of 3 LEED daylighting credits, confirming the effectiveness of climate-responsive, passive solutions in meeting high-performance building standards. The findings provide a replicable model for zero-energy retrofitting in institutional buildings, particularly in dense tropical urban contexts like Dhaka.

This research demonstrates that design modifications resulted in significant improvements in daylight accessibility throughout each upgrade in form and façade design. The alternative design framework demonstrated that implementing environmental techniques alongside architectural systems leads to optimal space efficiency. The first phase demonstrated that deep louvre placement minimised glare but generated darker environments and irregular illumination areas between objects. The introduction of the open central space and the addition of jury space in Phase 2 enhanced daylight availability while keeping the original louvres active. The third phase deployed an advanced adaptive architecture that integrated ETFE panels, leading to enhanced performance. This study critically examined the climatic and functional shortcomings of the existing building, highlighting the need for more context-responsive design solutions. By integrating data-driven methodologies, this research challenges conventional practices and advocates for more adaptive and efficient architectural solutions.

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THERMAL PERFORMANCE OF 3D-PRINTED CONCRETE WALLS

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ABSTRACT

The swift advancement of additive manufacturing within the construction industry has established a foundation for novel methodologies in the fabrication of structural and envelope components, characterised by enhanced efficiency, design adaptability, and material accuracy. Among these pivotal innovations, 3D concrete printing (3DCP) is distinguished as a revolutionary technique for the erection of walls and architectural features without the necessity for formwork, thereby minimising material waste and labour expenditures. With the increasing integration of 3DCP it becomes imperative to evaluate the performance of 3D-printed building components according to the regulatory standards and sustainability objectives. This paper investigates thermal performances of a prototype 3D-printed concrete wall based on the requirements of the UK's Approved Document L. Laboratory tests were conducted to assess the thermal properties of the concrete specimens followed by simulations in VOLTRA to ascertain the actual thermal performance of the prototype wall. The outcomes indicated an overall U-value of 0.23 W/m^{2}K that complies with the regulations. Thermal bridging was however identified as a major risk that could compromise the performance of 3DCP walls. Modifications to the internal configuration and geometry of the wall, composite layering, and insulation materials are expected to augment the overall thermal performance.

Keywords: 3D Concrete Printing (3DCP), Robotic Construction, Thermal Performance, Energy Efficiency.

1. Introduction

The global construction industry faces persistent challenges, including high accident rates, inefficiencies, significant labour dependency, and escalating costs, with formwork alone contributing up to 60% of total expenses and consuming 50-70% of overall construction duration (Li & Poon, 2013). In response to these enduring issues, additive manufacturing, particularly 3D Concrete Printing (3DCP), has emerged as a groundbreaking technology (Bos et al., 2016). This revolutionary technique is establishing new paradigms for fabricating structural and envelope components, characterised by enhanced efficiency, remarkable design versatility, and improved material accuracy (Ehle, 2003). A key advantage of 3DCP lies in its ability to construct walls and intricate architectural features without the need for traditional formwork, thereby substantially reducing material waste and labour expenditures inherent in conventional building practices (Ryu, 2013). Beyond the immediate economic and logistical benefits, 3DCP offers profound environmental advantages that align with contemporary sustainability imperatives. The technology facilitates significant reductions in material consumption, with reports indicating up to a 65% decrease in material costs compared to traditional methods. Furthermore, 3DCP actively promotes the integration of recycled construction materials, contributing to a reduced environmental footprint and fostering resource-efficient concrete construction (Wang et al, 2023; Han et al. 2021; Kaliyavaradhan et al., 2022). The inherent geometric complexity afforded by 3DCP enables the design of freely shaped architectural elements, opening avenues for low-cost, highly customized designs that were previously impractical or prohibitively expensive. This positions 3DCP not merely as an economic advantage but as a holistic solution, where efficiency gains in cost, time, and labour are deeply interwoven with broader sustainability objectives, including material conservation, waste reduction, and enhanced energy performance (Rehman et al., 2023; Dharmalingam et al., 2024).

The evaluation of thermal performance is crucial for ensuring that 3D-printed components meet regulatory standards and contribute to energy-efficient building practices (Choobineh et al., 2013). As 3DCP gains increasing global prevalence, a rigorous assessment of the thermal performance of 3D-printed building components becomes critically important (Li & Poon, 2013). This evaluation is essential for ensuring adherence to regulatory mandates and achieving overarching sustainability objectives (Navazo et al. 2016). Buildings represent considerable energy consumers, with their operational phase alone contributing approximately 27-28% to global energy-related carbon emissions, while the aggregate carbon footprint of the built environment is estimated to be around 39-42% when accounting for embodied carbon from construction materials (Teh et al., 2015). Consequently, the thermal characteristics of the materials employed in building construction have a direct impact on carbon emissions and highlight the pressing necessity for improved energy efficiency within the built environment (Estokova & Porhincak, 2012; Judkoff, 2008). The inherent layered structure of 3D-printed concrete presents unique complexities for thermal evaluation. Unlike conventional cast concrete, which is often considered a homogeneous material, 3D-printed concrete is characterised by multiple distinct interfaces formed during the layer-by-layer printing process (Dey & Panda, 2022; Cicione et al., 2021; Costanzi et al. 2018). This layered nature can introduce internal inhomogeneities, including potential voids, defects, and non-uniform heat transfer pathways, all of which significantly influence the overall thermal properties and performance of the component. The presence of cracks and interlayer gaps, which can arise from specific material mix requirements or printing configurations, is a notable characteristic of 3D-printed elements (Kaliyavaradhan et al., 2022, Khosravani & Reinicke, 2021; Rastogi et al., 2020; Aliheidari et al., 2018). These discontinuities can substantially diminish thermal performance by acting as detrimental thermal bridges, creating preferential pathways for heat flow. (Ge & Baba, 2015). While 3DCP offers considerable design freedom and material efficiency, the manufacturing process itself introduces thermal challenges that must be thoroughly understood, quantified, and mitigated. Failure to address these process-induced defects could prevent the full realization of the theoretical thermal benefits of 3DCP in practical applications (Jain et al., 2010; Lin & Banerjee, 2008). Evaluating the thermal performance of the building envelope is fundamental to ensuring reliable energy performance and achieving overall energy consumption reductions. Optimizing the thermal properties of the building envelope can lead to substantial energy savings, with studies indicating potential reductions in electricity consumption by up to 12% and overall energy consumption by 25% through improved insulation (Bouchlaghem, 2000; Korniyenko, 2015; Carlini et al., 2014). This directly supports global climate change mitigation efforts and the pervasive drive towards low and net-zero energy buildings. The discrepancy between current 3DCP performance and stringent regulatory requirements transforms regulation from a simple compliance hurdle into a powerful catalyst for research and development, compelling the industry to actively improve thermal performance and achieve superior energy efficiency (Tay et al., 2022; Parkin, Herrera & Coley, 2020).

The UK Building Regulations, specifically the Approved Document L (UK Government, 2024), lay out the criteria for thermal performance in this investigation. A vital stipulation within these regulations' states that newly constructed external walls in residential buildings must achieve a U-value that does not surpass 0.26 W/m^{2}K. This rigorous requirement establishes a clear and demanding benchmark for the thermal efficiency of innovative construction technologies like 3DCP. The current research aims to assess the thermal properties of 3D-printed concrete walls to verify their alignment with these national construction standards. This "regulatory gap" fosters advancements in material science and structural engineering for 3DCP, motivating both researchers and the industry to seek significant improvements in thermal performance to satisfy both legal and market expectations.

2. Literature Review and Inherent Thermal Characteristics of 3DCP

Thermal simulation constitutes an essential instrument in modern architectural design and engineering, providing the ability to forecast critical performance indicators such as energy consumption, carbon dioxide emissions, peak energy demands, and overall thermal comfort within edifices (Clarke, 1985). This predictive functionality is crucial for a multitude of applications, encompassing the design of new structures, the strategizing of retrofitting initiatives, adherence to energy regulations, and the acquisition of green building certifications (Cheng & Cao, 2014). The capacity to precisely anticipate the thermal performance of a building empowers engineers and architects to make judicious choices that enhance energy efficiency and occupant well-being from the preliminary design phases (Feldgoise, 1997; Roth, 1995). A prominent challenge in building energy modelling is the well-documented "performance gap," wherein the actual measured energy consumption of a structure can significantly exceeds at times by as much as 2.5 times the forecasted energy usage (de Wilde, 2014). This variance is predominantly ascribed to inaccuracies in the input parameters of the simulation models, which encompass characteristics of the building and HVAC systems, in addition to decisions executed by modelers (Dil, 1993; Walker, Siegel & Degenetais, 2001). The fidelity of these input parameters exerts a direct influence on the dependability of the simulation results.

2.1 Inherent Thermal Characteristics of 3DCP

Research consistently demonstrates that the thermal conductivity of three-dimensional (3D) printed concrete edifices is generally inferior to that of conventionally cast concrete. This attenuation is predominantly ascribed to the existence of voids, defects, and the intrinsic stratified architecture resultant from the additive manufacturing process (Sun et al. 2021; Marais et al., 2021). For example, empirical evidence indicates that the thermal conductivity of 3D-printed edifices may be diminished by 9.88% to 30% in comparison to that of cast concrete (Ibrahim et al., 2020). A particular investigation identified 3D-printed specimens exhibiting thermal conductivity metrics ranging from 0.343 W/mK to 0.668 W/mK, juxtaposed with 0.715 W/mK for traditional cast concrete (Sun et al. 2021, Lucio-Martin et al., 2021). The phenomenon of porosity emerges as a pivotal determinant directly impacting thermal conductivity. The stratified configuration of 3D-printed concrete frequently culminates in elevated porosity, especially at the interfaces between layers, as opposed to the mass of the printed layer itself or to conventionally cast concrete (Ganjian, 1990). The incorporation of air pockets or voids within the material matrix, which exhibit significantly reduced thermal conductivity relative to the solid concrete matrix, contributes to the discernible diminishment in overall thermal conductivity. Nonetheless, it is imperative to acknowledge that not all voids confer advantages for thermal insulation (Singh, Bharadwaj & Bansal, 1982). While entrapped air typically serves as a poor thermal conductor, excessive interstitial spacing or inadequately formed layers can engender substantial, interconnected voids and fissures that paradoxically act as thermal conduits, establishing preferential paths for heat transfer and ultimately compromising the overall insulation efficacy (Kaliyavaradhan et al., 2022). This underscores the essential requirement for regulated porosity and microstructural refinement in three-dimensional concrete printing (3DCP), rather than an oversimplified pursuit of increased porosity. The geometry, dimensions, and distribution of voids are as critical as their aggregate volume in ascertaining effective thermal performance (Sun et al. 2021; Ooms et al., 2021; Kruger et al., 2021).

Table 1: Comparative Thermal Properties: 3D-Printed Concrete vs. Cast Concrete

Construction Method	Thermal Conductivity (W/mK)	Porosity (%)	Dry Density (kg/m^3)
Cast Concrete	0.715 - 1.305	11.36 - 19.74	1802.02 - 2015.09
3D-Printed Concrete	0.343 - 1.242	6.81 - 26.96	1797.46 - 1982.21

Font: Zhang (2005)

Table 2 summarises the parameters that affect thermal properties of 3D printed concrete. This intricate relationship between printing parameters and resulting microstructure highlights a complex process-property feedback loop in 3DCP. Adjustments in printing parameters to achieve desired thermal properties might inadvertently affect other critical properties, such as mechanical performance or fresh-state printability. For example, reducing the extrusion rate to lower thermal conductivity might compromise the material's buildability. This necessitates a multi-objective optimization approach in 3DCP mix design and process control (Reinold et al., 2020).

Table 2: Influence of Key Printing Parameters on 3DCP Thermal Conductivity and Porosity

Printing Parameter	Specific Values/Ranges Tested	Resulting Thermal Conductivity (W/mK)	Resulting Porosity (%)	Observed Impact on Voids/Gaps/Density
Extrusion Rate	13g to 16g	0.455 to 0.668	Decreases (denser structure)	Greater material deposition, broader bead width, enhanced adhesion, lower porosity (Jonas & Chandra, 1971); Yamaguchi, Katou & Miura, 2001)
Printing Speed (Nozzle Travel Speed)	95 mm/min to 114 mm/min	0.515 to 0.407	Increases (more surface voids/gaps)	Smoother surfaces, reduced layer bonding, micro voids, gaps between layers (Booth et al. 2003; Hwang et al., 2006)
Nozzle Standoff Distance	6 mm to 8 mm	0.455 to 0.366	Increases (larger surface voids/gaps)	Formation of larger surface voids and gaps between printed layers Mejia & Moallem, 2003)
Distance Between Printed Lines (Horizontal)	7 mm to 9 mm	0.343 to 0.538 (varies)	Varies (optimum at 8mm)	Excessive spacing: voids/gaps. Minimal spacing: connected bubbles, increased porosity (Manners, 2003)
Number of	1, 2, 3 layers	Varies (2-layer	Varies (2-layer	Presence/absence of vertical

Printing Layers		often lowest)	often highest)	interlayers, self-weight compaction Scheel et al., 2000; Graebner & Azar, 1997).
Printing Path	Path I vs. Path II	Path, I lower	Path I higher	Differences in horizontal interlayer areas and associated porosity (Nauka & Yang, 2004).

Font: Jonas & Chandra (1971); Yamaguchi, Katou & Miura (2001)

3. Methodology

The primary objective of this ongoing research is to assess the thermal performance of a 3D-printed concrete wall utilising VOLTRA (v8.1.03), a transient thermal analysis software developed by Physibel. The fundamental aim is to compute the U-value of the wall and determine its compliance with the minimum thermal performance requirements prescribed by current national building regulations, particularly the stipulations outlined in the Approved Document L as established under the UK Building Regulations (UK Government, 2024). The methodological framework entails constructing and testing a model of a real-world specimen derived from a recently concluded trial in three-dimensional concrete printing (Image 1).

Figure 1: 3D Printed wall Sample with 1M Height.

Key thermal properties of concrete, such as thermal conductivity (λ), specific heat capacity, and density, are incorporated into the simulation model. These parameters are based on empirical values from the literature and data sheets obtained from the commercially available Sikacrete®-751 3D material, which includes results from laboratory thermal conductivity assessments. Table 3 summarises the parameters used for the simulations.

Table 3: Key VOLTRA Simulation Input Parameter.

Material / Properties	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (J/kg·K)
Concrete	0.706	1000.0	1000.0
insulation	0.022	1000.0	30.0

To ensure reproducibility, all simulation parameters were carefully defined and justified. The VOLTRA simulation necessitates a comprehensive array of input parameters to accurately model the transient thermal behaviour of a building element. These inputs are categorized as follows:

- Geometry: The building element's geometry is defined as three-dimensional rectangular shapes, often imported directly from TRISCO data. The input file specifies a grid unit of 0.025 m for X, Y, and Z dimensions. The total grid dimensions are derived from the maximum grid coordinates in the input file: 1.05 m (X), 0.4 m (Y), and 1.025 m (Z) (calculated from Xmax=42, Ymax=16, Zmax=41 multiplied by 0.025 m/unit). The detailed configuration is defined by various blocks within this grid. This ensures that the physical dimensions and configuration of the component are precisely represented in the simulation.

- Boundary Conditions: These parameters define the thermal environment surrounding the building element and are often time-dependent functions.
    - Internal and External Temperatures: The simulation used a constant external temperature of 0.0 °C and a constant internal temperature of 20.0 °C.
    - Heat Transfer Coefficients: The external heat transfer coefficient is 25.00 W/(m^2·K) and the internal heat transfer coefficient is 7.70 W/(m^2·K).

3.1 Laboratory Tests

The experimental evaluation of thermal properties commenced with the preparation of a moulded cube sample using Sikacrete®-751 3D, a single-component, cementitious mixture tailored for robotic extrusion. The sample was air-dried for a period of 30 days under ambient conditions to simulate in-situ curing effects. This was followed by a secondary conditioning phase in a heat chamber at 45 °C for five consecutive days to further stabilize internal moisture levels and replicate post-construction environmental exposure. After conditioning, the sample—measuring 20.0 cm × 20.0 cm × 3.7 cm and weighing 3334.00 g—was subjected to thermal conductivity testing in the Heat Flow Meter (HFM 446 Small), with data captured through NETZSCH software. Testing was conducted at a mean temperature of 10.0 °C with a thermal gradient of 20.0 K, yielding a measured thermal conductivity of 0.70551 W/(m·K) and a calculated density of 2252.7 kg/m^3.

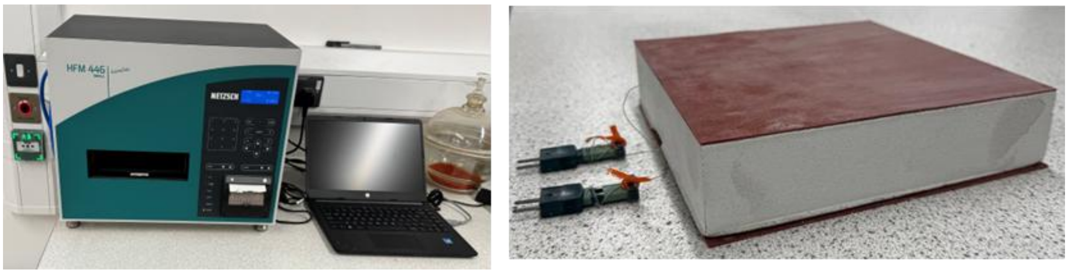
4. Results and Discussion

This section delineates the synthesized findings derived from both the laboratory assessments of thermal conductivity and the computational thermal simulations conducted in VOLTRA. The inquiry is organised into a bipartite framework: initially, laboratory assessments aimed at establishing the foundational thermal conductivity metrics of the 3D-printed concrete composite; subsequently, a thermal performance appraisal through simulations utilising the empirically acquired material characteristics.

4.1 Laboratory Testing and Thermal Conductivity Assessment

The preliminary stage of the investigation encompassed the quantification of the thermal conductivity of a three-dimensional printed concrete specimen produced using Sikacrete®-751 3D. The evaluation was executed at the SRI Laboratory utilising the HFM 446 Small Heat Flow Meter (Image 2) at an average temperature of 10°C, with a temperature differential (ΔT) maintained at 20 K. The results indicated a final thermal conductivity of 0.70551 W/(m·K).

Figure 2: a) Photograph of Lab Sample Before Testing (left), b) Heat Flow Meter Equipment (right).

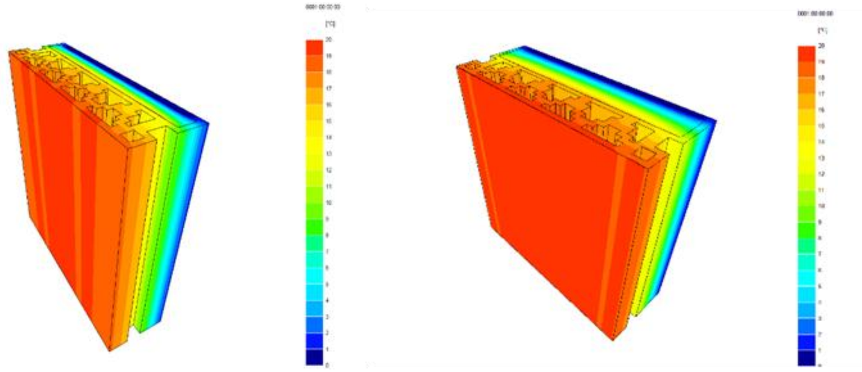


The specific input specifications for thermal simulations, especially regarding material characteristics such as density and specific heat capacity, imply that the HFM thermal conductivity measurement is a component of a wider, cohesive material characterization initiative. For materials such as concrete, where thermal performance is greatly affected by elements like moisture levels, type of aggregate, density, and porosity, a thorough material characterization (going beyond merely thermal conductivity) is crucial to achieve accurate results. The lab testing, although primarily centred on thermal conductivity, likely also included the assessment of these additional properties (e.g., density evaluation, moisture content analysis) to deliver a complete and coherent dataset for the VOLTRA simulation.

4.2 VOLTRA Simulations (Thermal Performance)

The VOLTRA model (Image 3) emulated the actual configuration of the three-dimensional printed prototype wall, measuring 1.0 m in length (X), 0.40 m in width (Y), and 1.0 m in height (Z), and was established using a grid unit of 0.025 m. Utilising a 75 mm cavity insulation resulted in an overall heat loss of 7.21 W. Considering a surface area of 1 m^2 (width: 1m × height: 1m) and a temperature differential of 20 K, the corresponding U-value was derived as follows**: U-value = Q / (A × ΔT) = 7.21 W / (1 m^2 × 20 K) = 0.3605 $W/m^2·K$**. This value surpassed the permissible limit defined in UK Building Regulations Part L. In a subsequent iteration, enhancements were made to both the cavity depth and the insulation thickness. The computed steady-state heat transfer through the wall was quantified to be 4.62 W. Leveraging this output, the U-value was calculated based on a surface area of 1 m^2 and a temperature differential of 20 K as follows: **U-value = Q / (A × ΔT)** heat loss (Q) of 4.62 W, a sample area (A) of 1 m^2, and a temperature gradient (ΔT) of 20 K **= 4.62 W / (1 m^2 × 20 K) = 0.231 $W/m^2·K$**. The calculated U-value is below the threshold value of 0.26 $W/m^2·K$ specified in the UK Building Regulations Part L, thereby suggesting that the wall possesses the potential to comply with regulatory standards under optimal conditions.

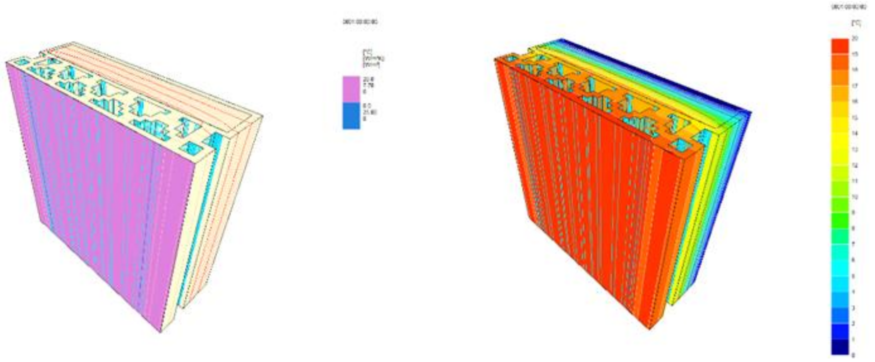
Figure 3: a) 75 mm Cavity (left); b) 125mm Cavity (right) Heat Flow and Temperature Distribution.



4.3 VOLTRA Simulations (Edge Effects and Thermal Bridging)

Although the average thermal performance appears to be promising, the simulations revealed significant thermal/cold bridging, particularly pronounced at the edges where openings are meant to be installed. This is due to the lack of thermal break in these areas. Unlike traditional brick/block cavity walls, where thermal breaks are considered to reduce thermal bridging in and around opening areas (i.e. doors/windows), for practical reasons, 3D printed walls need to be continuous which limits the ability to create gaps between inner and outer layers of the printed cavity walls resulting in potentially significant compromise in thermal performance of the 3DP walls due to thermal bridging. Thermal bridging could not only affect the overall thermal performance of the walls but may also lead to increased risks of condensation and mould growth around the opening areas. Within this specific context, the occurrence of cold bridging at the edges and vertical joints of the printed wall unequivocally underscores the necessity for additional geometrical modifications and material adjustments that are imperative to effectively mitigate heat losses through thermal pathways.

Figure 6: a) Thermal Bridge (left); b) Thermal Gradient Arrows at Edges (right).



Some of the following design and material modifications may improve the abovementioned issues. Segmented Cavities: Research has shown that breaking up large wall cavities into smaller segments can significantly reduce heat transfer and improve thermal efficiency. Intricate Infill Designs: The unique design flexibility offered by 3DCP allows for the integration of complex internal shapes, like hexagonal, double-row honeycomb, or lattice patterns. These specific configurations trap air within the wall, acting as an effective form of passive insulation and increasing the wall's overall thermal performance. Filling Materials: The empty cavities can be filled with lightweight granular insulating materials such as expanding polystyrene (EPS) beads, loose-fill perlite, or blown mineral wool. These strategies have been shown to improve thermal performance by significantly enhancing the wall's U-value, leading to lower energy usage.

5. Conclusion

This investigation rigorously examined the thermal performance attributes of a three-dimensional-printed concrete wall through the integration of laboratory-based thermal conductivity evaluations and advanced simulation-driven thermal modelling. The principal objective of this research was to assess the degree to which such pioneering wall structures can comply with the stringent criteria established by the UK Building Regulation Part L, with a specific emphasis on the critical U-value target of 0.26 $W/m^2{\cdot}K$ as mandated for newly constructed external residential walls. The thermal conductivity measurement obtained from the lab tests for the concrete material was recorded as 0.70551 W/(m·K) provided empirical foundation for detailed thermal simulations. The simulations indicated an overall U-value of 0.231 $W/m^2{\cdot}K$ for the wall with a cavity infilled insulation of 125mm, which was significantly below the threshold. There is therefore a tangible potential for 3D-printed walls to successfully meet national thermal performance standards. Nonetheless, the simulation results also underscored the concerning challenge of thermal bridging, particularly at critical interfaces such as the edges and corners of the walls, that can compromise the overall thermal efficacy and thus necessitates resolution through improved design. Looking forward, future research initiatives will seek to refine the geometrical configurations of the walls, improve the formulations of the materials employed, and further integrate insulation strategies to optimize the performance.

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CHAPTER 4

MASS CUSTOMIZATION AND AFFORDABILITY

AI SHIFT IN PREFAB HOUSING: OPPORTUNITIES AND SPECULATIVE FUTURES

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ABSTRACT

This paper explores the potential role of artificial intelligence (AI) in transforming prefabricated housing through enhanced design, customization, and decision-making. Adopting a speculative design methodology grounded in current literature and precedents, it examines how AI can support mass customization by enabling user participation and predictive feedback during design-to-production workflows. Two areas are emphasized: AI-driven generative design platforms that empower end-users to co-create layouts, and predictive tools that provide real-time feedback on performance, cost, and feasibility. A conceptual model is introduced to illustrate how these processes interconnect. Although empirical testing is beyond the scope of this work, the paper outlines speculative scenarios to provoke reflection on AI's role in reshaping prefabrication from standardization to responsive customization. The discussion concludes with a roadmap for future research, highlighting the need for case studies, prototyping, and ethical evaluation to validate and advance AI-enabled mass customization in housing.

Keywords: Architecture, Prefab housing, Artificial Intelligence, Mass customization

1. Introduction

Prefabricated housing, often referred to as prefab, is a method of construction in which building components are manufactured off-site and assembled on location. This approach is increasingly recognized for its potential to streamline construction, reduce waste, lower costs, and shorten project timelines (Smith, 2010; Kieran & Timberlake, 2004). Throughout the last decades, prefab has gained remarkable interest. It is sought as a potential model to offer affordable and sustainable housing, as technological advancements continue to enhance its flexibility and architectural quality (Pan, Gibb & Dainty, 2008).

In parallel, Artificial Intelligence (AI) has grown exponentially, evolving from narrow applications to wide-ranging capabilities across industries. While initially recognized for classification and pattern recognition tasks, AI now plays an increasing role in the creative industries sector. AI's applications rapidly expand in the built environment—from automating design iterations to optimizing performance and enabling new forms of human–machine collaboration (Del Campo et al., 2022). The potential applications of AI now extend far beyond generating images or texts, as it promises to transform how we design, deliver, and hypothetically customize the built environment.

This paper explores how AI could reshape the prefab housing sector by supporting more user-driven customization and more data-informed early-stage design decisions. The research takes a speculative and theoretical approach to examine two main areas: (1) AI-enabled design platforms that allow users to co-design layouts and configurations towards customization, and (2) the role of predictive AI systems that offer real-time feedback on performance, cost, and constructability during early design stages.

The paper is structured as follows: First, a brief theoretical background covering prefab housing, customization, and the current evolution of AI in architecture. Second, an outline of the methodology and speculative design model used. Third, exploring the two main areas of opportunity: customization and prediction. Last, conclusion and discussion of future research directions.

2. Theoretical background

Prefabrication, or prefab, refers to the off-site production of building components that are later transported and assembled on-site, offering faster delivery, reduced waste, and lower costs (Smith, 2010; Pan et al., 2008). Contemporary systems are increasingly moving beyond standardized models as digital design and production tools enable flexible, customized solutions at scale. At the same time, AI tools have advanced from narrow classification tasks to generative, predictive, and optimization roles in architecture, positioning it as both a creative partner and a decision-support tool (Chaillou, 2022). Recent studies highlight AI's potential to automate layouts, optimize components, and improve risk management in prefabricated construction (Yu et al., 2020; Chen et al., 2021; Wang et al., 2022), yet most focus on efficiency rather than user-centered design. This paper addresses that gap by proposing a speculative framework in which AI acts as both a generative engine and predictive advisor, supporting mass customization and reframing prefabrication as a responsive, user-driven process.

2.1 Prefabrication and Customization

Recent research on mass customization in housing has predominantly emphasized technological dimensions, reflecting the intrinsic connection between customization and advancements in design and fabrication technologies. As Eid Mohamed and Carbone (2022) outlined, the literature reveals many concerns, including homebuyer profiling, computational design generation, and integrating design and production through digital collaborative platforms. Additionally, several studies explore the role of emerging fabrication tools and machinery in enabling the efficient production of highly varied housing components. Within this diverse body of work, authors discuss the technological, economic, and cultural barriers that continue to challenge the implementation of mass-customized prefabricated housing (Eid Mohamed & Carbone, 2022).

In the context of the prefab housing industry, typically considered a promising domain for the adoption of mass customization, many leading global producers have formed collaborative alliances with architects, computational designers, and fabrication technologists. These partnerships aim to enhance design, visualization, and production workflows in response to evolving market demands. A central objective has been to offer customizable housing solutions that address homebuyers' social and cultural preferences while maintaining affordability, quality, and environmental performance. As part of these efforts, the industry has increasingly explored internet-based interactive configuration systems as practical tools for engaging and communicating with prospective clients (Eid Mohamed & Carbone, 2022).

2.2 AI Expanding Influence in Architecture

AI is rapidly evolving and expanding its impact across disciplines. Initially developed for narrow applications such as image recognition, natural language processing, or classification tasks, AI can augment human creativity, reasoning, and problem-solving in new and profound ways (Chaillou, 2022). In architecture, researchers increasingly explore AI as both a tool for automation and an active collaborator in the design process. As highlighted in *Artificial Intelligence and Architecture: From Research to Practice* (Chaillou, 2022), AI systems are being integrated into workflows to generate, evaluate, and refine design proposals, often uncovering solutions that might remain inaccessible through conventional methods. Designers use AI as a generative tool to produce countless spatial and formal variations based on set parameters; as a predictive system that estimates performance metrics such as cost, energy efficiency, and structural behavior; and as an optimization engine that navigates complex trade-offs in real time. This shift positions AI as more than a novelty or technological add-on; it signals its emerging role as an enabler of end-to-end design-to-production workflows, offering the potential to rethink the building lifecycle from concept to fabrication and ultimately transforming how architecture is conceived, produced, and experienced (Chaillou, 2022).

2.3 Intersection of AI and Prefab

Multiple research efforts have recently been published, reflecting a growing interest in the intersection of AI and prefabricated architecture. Publications focus on how AI can address the challenges of efficiency, automation, and sustainability in construction. (Li et al., 2021; Chen et al., 2021; Wang et al., 2022). Studies have highlighted AI's role in automating layout generation, optimizing component design, and improving decision-making across design-to-production workflows (Yu et al., 2020; Chen et al., 2021). These works demonstrate how AI can enhance modular construction through real-time data analysis, performance prediction, and adaptive design strategies (Wang et al., 2022; Li et al., 2021). This expanding body of knowledge signals a shift toward more data-informed, responsive approaches to prefab housing, positioning AI as a key enabler of next-generation building systems.

3. Speculative Methodology and Conceptual Model

This paper adopts a speculative design methodology to explore how AI could enable mass customization in prefabricated housing. Speculative design, as defined by Galloway and Caudwell

(2022), is not aimed at prediction but at opening debate by constructing “what if” scenarios that encourage reflection on alternative futures. In this study, scenarios were developed through a three-step process: (1) a brief, yet critical literature review on AI in design, prefabrication, and mass customization; (2) the construction of speculative narratives informed by existing AI tools, housing market needs, and precedents in computational design; and (3) the synthesis of these insights into a conceptual model that illustrates potential workflows for AI-enabled customization. The resulting framework positions AI as a catalyst for shifting prefabrication beyond standardized efficiency toward responsive, user-driven solutions. By combining literature-based analysis with design-led inquiry, the approach highlights the potential of human–machine collaboration to reshape prefab housing while provoking discussion on its implications for practice and future research.

3.1 Literature-Based Reflection

While exploring the intersection of AI applications and prefabricated construction, recent studies highlight the capacity to support prefabrication processes by automating design generation, optimizing components, and enhancing decision-making at various stages of the design-to-production workflow. Pan et al. (2022) conducted a systematic literature review on Artificial Intelligence and Robotics (AIR) in prefabricated and modular construction, analyzing 97 journal publications. The review is structured around four research questions that guide the synthesis of prior studies within a coherent framework. Building on this analysis, the paper outlines five key directions for future research and practice: the integration of AI and robotics (AIR) for large-scale modularization, multi-dimensional project management, intelligent post-construction management, enhanced interdisciplinarity and interoperability, and the pursuit of solutions that extend beyond purely technical aspects. While the paper does not explicitly address mass customization, advancing AIR integration could provide a foundation for more flexible and responsive prefabrication workflows. Such integration is critical for enabling mass customization in housing where design, production, and assembly processes adapt dynamically to diverse client needs, contextual conditions, and user preferences.

Wang (2024) presents the development of a decision support system for prefabricated buildings that integrates artificial intelligence (AI) with advanced data processing techniques. The system is designed to assist designers, engineers, and decision-makers by analyzing complex data sets related to prefabricated construction, including material selection, structural design, and cost factors. The AI algorithms help process large-scale data efficiently, offering predictive insights and optimization recommendations to improve design accuracy, construction efficiency, and resource use. The study demonstrates that such AI-based decision support systems can enhance the intelligence and reliability of prefabrication processes. However, it notes the need for ongoing refinement to address the complexities of real-world applications and diverse building requirements.

Yu et al. (2020) review design automation efforts in modular construction, emphasizing how AI techniques can support layout generation and component optimization but highlighting the need for further work on integrating user preferences and adaptive design. Similarly, Li et al. (2021) examine AI and BIM-based risk management in prefabrication, showcasing how AI can proactively identify and mitigate production risks. These studies indicate AI's growing role in transforming prefabrication from static standardization to more responsive, data-informed practices.

Recent research on the role of AI in prefabricated housing has primarily focused on enhancing the production workflow through automation, optimization, and risk management. However, while these studies showcase AI’s capacities for streamlining workflows, there is still a gap in exploring AI’s full potential toward user-driven design variation and end-to-end customization, where individual homebuyer preferences shape the design-to-production workflow. The power for AI to enable genuinely flexible, adaptive housing solutions that respond dynamically to unique user needs remains an underexplored frontier in current research.

Based on these insights, the following section introduces a series of speculative design scenarios that aim to imagine future applications of AI for generative customization, where housing designs are tailored in real time based on user input and predictive design. It also integrates how AI could anticipate performance, cost, and constructability outcomes to guide decisions. This exploration aims to provoke reflection on how AI might help reshape prefab practices, thus move beyond standardization toward truly individualized, data-informed mass customization.

3.2 Speculative Design Scenarios

Speculative design as a research method is a means of asking questions, opening critical dialogue, and engaging with uncertainty. Galloway and Caudwell (2022) describe speculative design as a research method that focuses on generating debate, reflection, and alternative perspectives on complex societal, technological, or environmental challenges. Importantly, speculative design encourages researchers and designers to engage with complexity and ambiguity rather than seek quick solutions or clear conclusions (Galloway & Caudwell, 2022). In architecture, this approach allows researchers to question dominant paradigms and imagine new relationships between people, technology, and the built environment. Instead of producing buildable designs, speculative scenarios function as conceptual narratives or prototypes that provoke reflection on potential futures.

Within this study, speculative design scenarios are proposed to envision how AI to explore how AI could enable mass customization at different stages of the prefabricated housing process. The scenarios are derived from the literature review, analysis of existing AI tools and digital configurators in related fields, and consideration of housing market demands for greater flexibility and personalization. Framed as design narratives, the scenarios test “what if” futures in which AI acts simultaneously as a generative engine and predictive advisor, enabling more responsive, user-driven housing.

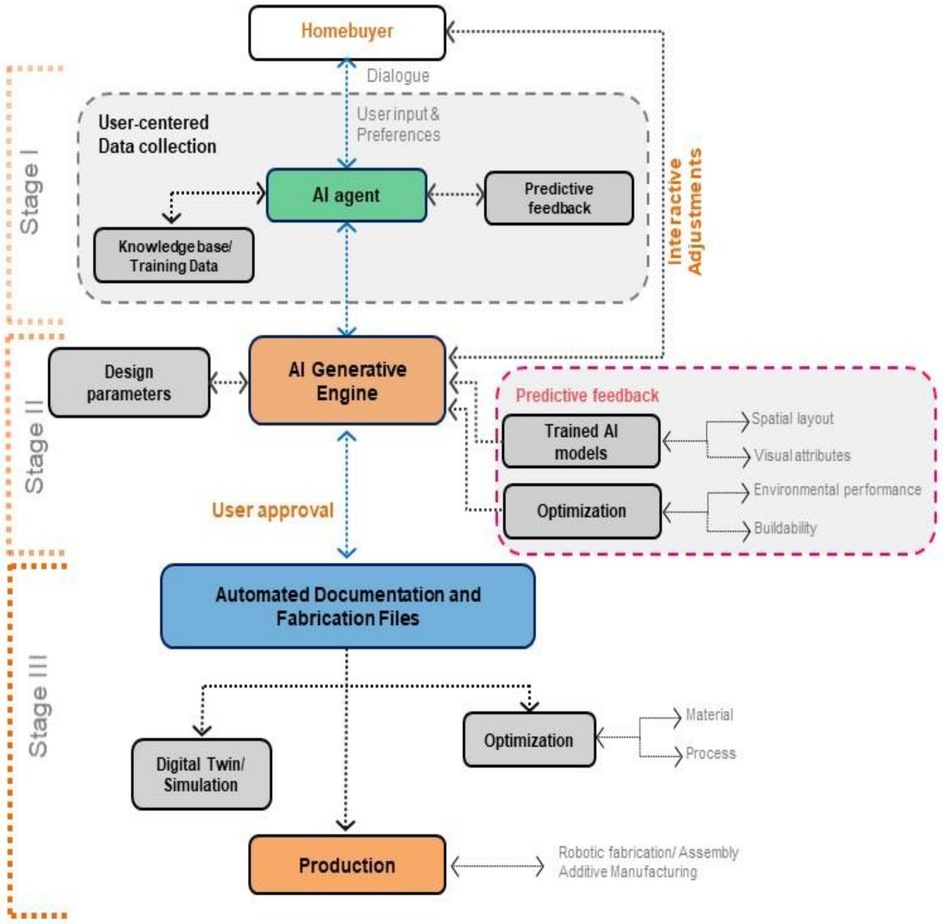
By situating these scenarios within precedents in computational design, product configuration systems, and human–AI collaboration, the study develops a foundation for the conceptual model introduced in the following section. The goal is not to provide immediate technical solutions, but to use speculation as a tool to interrogate opportunities, challenges, and implications of integrating AI into prefab workflows.

4. A Model for AI-Enabled Mass Customization

Building on the literature and speculative scenarios outlined earlier, this section synthesizes a conceptual framework for how AI can enable mass customization in prefabricated housing. The model positions AI not only as a tool for automation or optimization but as an integrated medium that supports both creative and rational dimensions of design. It emphasizes two interconnected capacities through which AI could reshape prefabricated workflows: (1) AI-driven generative customization, which dynamically produces housing variations tailored to user needs and contexts; and (2) AI-supported predictive feedback, which provides real-time evaluation of design feasibility, performance, and cost. Together, these components establish a pathway toward flexible, data-informed, and scalable housing solutions that merge industrial efficiency with user-centered design.

To capture this process, Figure 1 presents the proposed AI-driven mass customization workflow, synthesizing these two components into a structured framework. The model unfolds in three stages:

(I) user-centered data collection, which gathers preferences, budgets, and contextual constraints; (II) an AI-assisted generative engine with a predictive feedback loop, which iteratively produces design alternatives while testing feasibility and performance in real time; and (III) automated documentation and production integration, where validated solutions are translated into prefabrication-ready outputs. This workflow highlights the continuous interaction between user input, AI-driven generation, and predictive evaluation as the foundation for delivering scalable, user-responsive housing



4.1 AI-driven generative customization

AI-driven generative design tools employ techniques such as generative adversarial networks, diffusion models, and deep learning to rapidly produce and optimize design alternatives. These systems explore vast design spaces, balancing objectives such as aesthetics, energy performance, and material efficiency (Channi, Kaur, & Kaur, 2025). By integrating simulation and feedback, they refine solutions while keeping architects in control of decision-making, thereby enhancing creativity and supporting sustainable, data-driven outcomes.

Applied to prefabricated housing, such tools could generate tailored layouts and material configurations based on user-defined parameters, including spatial organization, performance targets, and cost preferences. This enables mass customization that balances individual choice with industrial feasibility. Beyond technical optimization, AI can also integrate socio-cultural values, learning from local precedents or environmental data to produce context-sensitive solutions. As Leach (2021) notes, this positions AI as a creative partner, while Chaillou (2022) argues it allows a shift from fixed templates to adaptive systems. In this sense, generative customization moves beyond superficial variation, enabling genuinely diverse and responsive housing environments.

4.2 AI-supported predictive feedback

A second critical component is predictive feedback, which integrates AI into early design decision-making as an intelligent advisor. By evaluating design alternatives against multiple criteria, AI systems can provide real-time estimates of cost, energy use, construction timelines, and structural feasibility (Chen et al., 2021). This feedback loop helps homebuyers and fabricators explore trade-offs before committing to production, ensuring that customized solutions remain within budget and performance targets. Predictive tools also enhance risk management and reduce errors, key challenges in industrialized construction (Eid Mohamed & Carbone, 2022).

5. Conclusion, Reflection, and Future Work

Over the years, as digital design and fabrication tools have advanced, many researchers have devised ways to implement mass customization in the housing sector. However, while industries like consumer goods have successfully embraced these ideas, the prefabricated housing sector has struggled to overcome the challenges needed to adopt this production model despite its suitability to adopt such an approach. Today, the rapid growth of AI in design signals a new wave of opportunities to revisit and achieve mass customization in housing.

This paper explores the speculative potential of AI to support mass customization in prefabricated housing. It proposes a conceptual model that combines AI-driven generative design and predictive feedback. The study suggests that AI could help shift prefabrication from a standard, efficiency-focused process to one that offers more flexible, user-centered, and context-sensitive housing solutions.

The model provides a starting point for future research, showing how AI could act as a creative partner and advisor that helps guide decisions from design to production. However, bringing this vision to life will require collaboration across disciplines, better data systems, and careful consideration of AI's social, cultural, and ethical impacts in housing design. Future work should focus on developing and testing AI-based customization systems, ensuring they are transparent, inclusive, and responsive to real-world needs. In the long term, integrating AI into prefabrication could help deliver more adaptable, sustainable, and meaningful housing for many communities.

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PERFORMANCE-BASED CELLULAR AGGREGATION: GENERATIVE METHOD FOR THERMAL AND DAYLIGHTING IN HIGH-DENSITY HOUSING - HOT AND DRY CLIMATE, AHMEDABAD, INDIA

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ABSTRACT

In the Global South, the rapid pace of urbanisation has significantly increased the need for housing. The hot and arid climate of Ahmedabad, India, has spurred a growing demand for housing solutions that are both efficient and sustainable. In such settings, it is essential to optimise solar radiation exposure along with optimal daylighting to create energy-efficient buildings and improve the indoor thermal comfort of residents. This study presents a generative approach for performance-based cellular aggregation of solar and daylighting performance in high-density housing during the initial design phase. Utilising a computational framework, the proposed method models and simulates the interaction of forms for annual solar insolation and daylighting performance. Three experimental series were conducted: open court, U-shaped, and street typology. The street type was the best option for solar and daylighting performance at the selected site. The findings of this study underscore the significance of performance, energy efficiency, and variety in high-density mass housing, which contribute to sustainable development goals and liveability in hot and dry climates. The application of this approach in Ahmedabad illustrates its potential to inform design decisions that reduce environmental impacts, and could be applied to other climatic contexts around the world

Keywords: Cellular Automata, High-density housing, Hot and Dry climate, Solar and Daylighting performances

1. Introduction

High-density housing represents a strategy for sustainable urban development, wherein land is utilized efficiently as a finite resource. In Asia, high-density architecture is predominantly characterized by a limited array of building types that closely align with the site's maximum development potential (Herr & Kvan, 2007). This often results in monotony, a fixed typology of units, and a lack of identity, coupled with low-performance structures. As a potential architectural design approach to address this issue, we investigated the application of a generative computational method using cellular automata (CA) at the initial design stage. This study seeks to explore a method for generating variance and identity while achieving thermal performance objectives for a group housing typology through a performance-based cellular aggregation (PBCA) of a generative design method, considering the constraints of climatic context and building regulations in India.

Given the complexity and diversity inherent in the design process, group housing or apartment buildings present a promising domain for automation due to strong interdependencies, such as parts-to-whole and whole-to-parts relationships, and the repetitiveness of units (Jansen et al., 2023). The application of CA to architectural design offers a lower-level rule system, acting on a more elemental deconstruction of architectural space than the topological methodology adopted by many current spatial generators (Birkhauser, 2002). CA could serve as a novel method for generating housing massing for specific performance criteria in the early design phase by arranging cells. The primary characteristics of a CA generative system include the production of a vast array of solutions and the generation of complex morphologies by applying simple rules to address the majority of constraints (Neumann, 1963). As a generative design support, CA is perceived as a pattern generator, facilitating the exploration of formal composition techniques (Chase, 2005).

In the realm of generative design, several attempts have been made to employ CA as a design support in the conceptual stage of the design process. These approaches are typically based on CA models adapted from other fields of study, which predominantly utilize CA as a simulation mechanism rather than as generative design support (Coates, 2010; Oxman, 2008). CA is an animation of cell arrangements; however, in this study, we attempted the aggregation of cells for high-density housing. Herr (2008) proposed that cellular automata can be more effectively utilized by adapting them to architecture rather than employing classical cellular automata applications (such as Conway’s Game of Life). Previous studies on cellular automata/aggregation for performance-based generative housing design are exceedingly rare, particularly in the context of hot and dry climates. Despite the growth and increased popularity of generative design approaches over the past decade, they have been scarcely explored in CA. Furthermore, existing work in this field has typically been confined to the scope of single projects, and no theoretical framework has yet been established (Herr & Ford, 2016). This study aims to apply CA in the context of early conceptual design, where performance-based CA may assume a different role than in previous studies.

Unlike the parametric method, the results of CA cannot be expected, which offers an interesting and rich platform for developing possible architectural patterns for high-density housing based on performance criteria. In this study, multiple scenarios were developed based on the simple connection rules of cell aggregation with a varied series of experiments.

2. Methodology

This study adopts a design-based research approach informed by generative design methodologies, particularly utilizing PBCA for architectural form generation. Drawing from literature on computation design, parametric modelling and performance-based design in high-density urban housing, the study integrates environmental performance metrics into early –stage design generation. The approach is situated within the performance-driven generative design paradigm, where design options are created and iteratively evaluated against environmental and spatial criteria. The overall methodology flowchart is shown in Fig. 1.

The study is structured in three key phases:

a) ***Rule Definition and Design Framework:***
   - Define aggregation rules for mid-rise housing typologies based on spatial adjacency, access, privacy, and regulatory constraints.
   - Integrate environmental performance requirements, including solar insolation thresholds and daylighting levels per green building standards in Indian - ECBC and GRIHA
   - Establish a 2-hectare plot in Ahmedabad (hot-dry climate) as the design context.

b) ***Generative Scenario Development:***
   - Use parametric design tools to generate multiple massing configurations based on the defined cellular aggregation rules.
   - Develop three design scenarios that vary in aggregation logic and spatial distribution strategies, while ensuring feasibility under zoning, FAR, and building regulations.

c) ***Performance Evaluation and Selection:***
   - Evaluate each scenario using the following metrics:
     - ▪ Maximum Floor area
     - Annual Average Envelope Insolation (AAEI)
   - Apply daylight filtering to determine Window-to-Wall Ratio (WWR) for each façade orientation using generative filtering methods aligned with green building performance targets
   - Select optimal configurations based on a balance of density, environmental performance, and space planning flexibility

Each of the three scenarios explores a different spatial strategy:

- Series -1 – Court type: Massing concentrated on the peripheral with an central open space and solar exposure
- Series – 2 – U–shaped -dispersed Clusters: Scattered volumes around a central open space that prioritize cross-ventilation and modularity
- Series - 3 – Street type: A terraced massing strategy that follows a north-south solar optimization logic

These variations test the design's ability to achieve net zero energy, spatial diversity, and potential customization at scale in the hot and dry climatic context of Ahmedabad. The following are the project frame work: Climatic context, Development control rules, design requirements, simulation tools and green building regulations.

2.1 Climatic context

The region Ahmedabad is situated in western India along the banks of the Sabarmati River, Lt 72.6276 Lat 23.0766 Long 72.6276. Ahmedabad experiences a semi-arid hot climate. According to the Köppen climate classification, Ahmedabad has a hot semi-arid climate (BSh). The average temperature of the city ranges from 12 to 41 °C. The hottest period in summer is from March to July, with a minimum average temperature of approximately 23°C and maximum temperature of 43°C. The annual cumulative horizontal solar radiation is 1980.26 kwh/m^2. The site map and annual average dry-bulb temperature are shown in Figs. 2 and 3, respectively

Figure 1: methodology flowchart

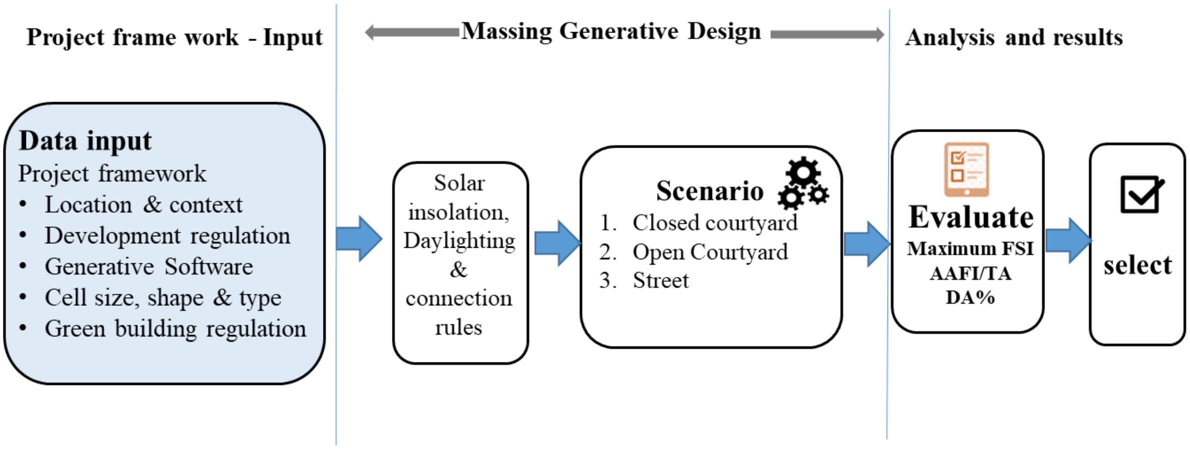


Figure 2: design site with dimension

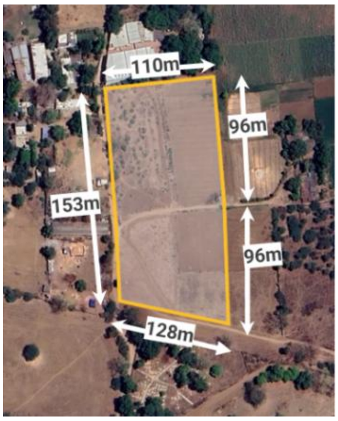
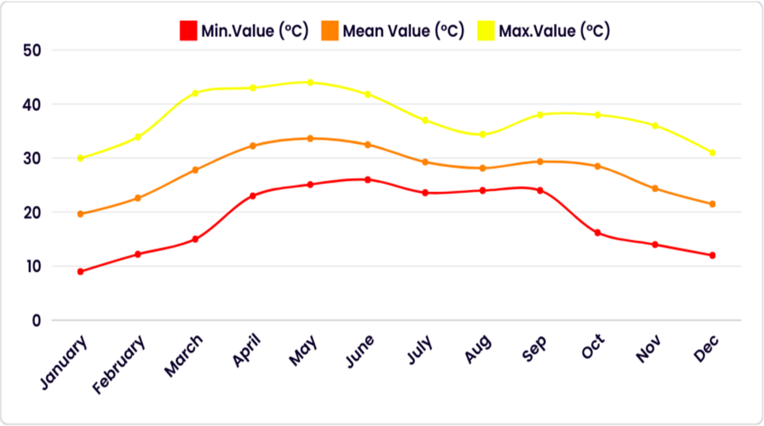


Figure 3: Annual average dry bulb temperature of Ahmedabad city.



2.2 Development control rules

Table1: Permissible development control rules applicable for the proposed site as per AUDA [20]

Site area	20249	sqmt
Permissible FSI	1.8	
Permissible Total Built-up area (TBA)	36448	sqmt
Minimum Front set back	4.5	m
Minimum Rear and Side setback	3	m
Maximum building height	25	m
Minimum Plot coverage	40%	
Minimum setback between blocks	6	m
Common plot / reserved open space @10%	2025	sqmt

2.3 Site and Design Requirements

The site has longer sides facing east/west with an access road 12 m wide and a total area of 20249 m^2.The design required for the selected samples site as per the development control rules as in table 2

Table 2: Design requirements

site area	20249	sqmt
Plot width	110-128	m
Plot depth	153-192	m
Total no of housing units	250	units
Density	125	DU/Hectare
3 bed room units (40%) @ 120 sqmt	100	units
2 bed room units (40%) @ 100 sqmt	100	units
1 bed room units (20%) @ 80 sqmt	50	units

2.4 SOFTWARE FOR SIMULATION

Ladybug and Honeybee are free open-source environmental plugins for Grasshopper3D. Solar incidental analysis was performed using Ladybug. Daylighting analysis were performed using Radiance (RAD), which was accessed through the interface of Honeybee Plus (HB +), a plugin for Grasshopper. *WASP* plug-in: WASP by Dr. Rossi is a type of grasshopper component with each of these cells/parts provides basic information for the discrete–aggregate process, including geometric orientation, link position, and orientation (Rossi & Oliver, 2017). In addition, optimizations were conducted using a genetic algorithm through the Galapagos interface.

2.5 GREEN BUILDING REGULATIONS

For the solar incidental analysis, the facade-to-floor area ratio (FA: TA): Energy-efficient façade design: ≤ 0.4 for energy efficiency (GRIHA V19, 2019). Roof-to-Facade Ratio: Balance between roof and façade: Preferably ≤ 0.5 [(GRIHA V19, 2019)]. The Shading Coefficient (SC): Reduces heat through glazing: For glazing, ≤ 0.4 is recommended (ECBC Chapter 5, 2017). For Daylighting performance, As per Criterion 10 alternative 2 of daylight appraisal demonstrated through simulation. The project meets the mean DA (Daylight autonomy) requirement (>300 lx) for 25 percent of annual analysis hours for residential buildings for 100% of the habitable spaces as a mandatory requirement (GRIHA V19, 2019).

Table 3: The simulation assumptions for daylighting analysis

Blinds & shade	Blinds, shades, or internal partitions are excluded from the model
Surface reflection	The ceiling, floor, and wall reflectance were 80 %, 20%, and 50 %, respectively.
The analysis plane	0.8 meters.
Analysis period	8 am to 6 pm, for a total of 3650 hours
Analysis Grid	1 x 1 meter
Sky Component	CIE uniform sky for Chennai location

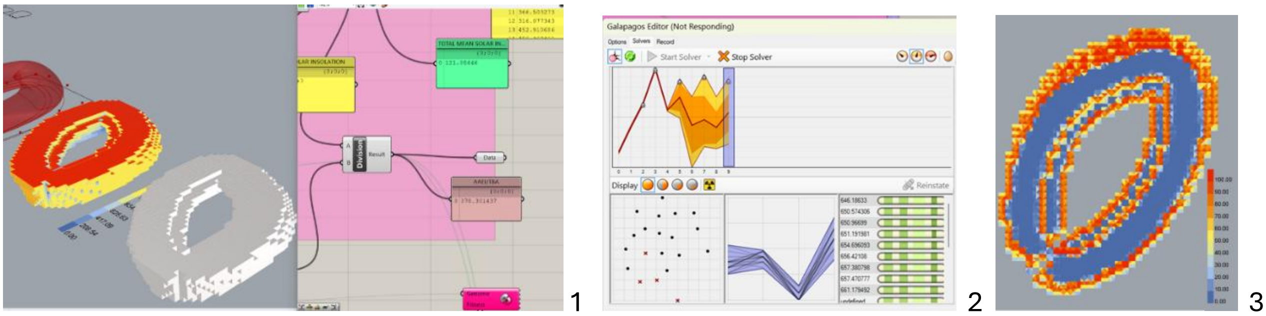
3. EXPERIMENTS

The major characteristics of a CA generative system are the production of a vast number of solutions and generation of complex morphologies by applying simple rules to cope with the majority of constraints (Caldas, L ,2008). The experiments or scenarios represent the complexity of the architectural form by the implementation of an entirely new and, in our view, a more appropriate methodology of parallel, nonlinear information development. Three scenarios of different typologies were tested based on the basic connection rules. Series 1 is the central court type, series -2 open or U-shaped, and series 3 is street type by arrangement of two blocks parallel. Parametric optimisation was performed using the Galapagos tool to identify the ideal aggregation of cells with low average annual facade solation (AAFI) relative to the total build area (TBA). For daylighting requirements of DA >25% with optimisation of WWR % for each orientation of the generated mass. This process demonstrates the power of performance-driven generative design in achieving sustainable housing solutions tailored to local climatic contexts

3.1 SERIES -1

In the buildable area, a closed parametric spline was created and extruded to a proposed height of 25m or G+7 floors, as shown in Table 1. This curve was refined using the generative method in Galapagos for solar radiation. Four-section parametric profiles were projected onto the refined spline through reference points to create a rail mesh by sweeping. The location and profile of the four sections are selected for the best solar insolation of the rail mesh results using the generative method in Galapagos. A closed cell of size 6.4,6.4, 3.2 is created as an aggregation cell in Wasp. With vertical and horizontal connections of these cells, the mass is aggregated within the rail mesh for the best solar insolation results in Galapagos, as shown in Fig. 4. The overall process is illustrated in Fig 5. By assigning WWR % to each cell for each orientation in the honey bee daylight opening configuration and selecting the best result for each floor of the massing by Galapagos results.

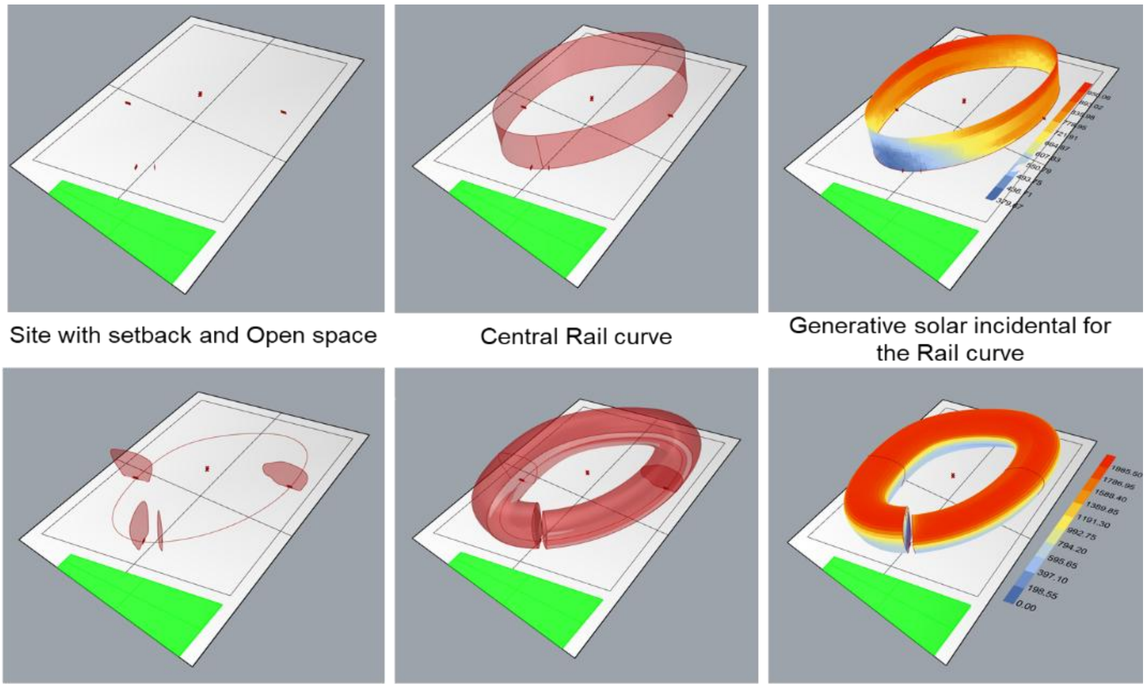
Figure 4: Image for Series-1 : **1.** Solar insolation and massing design of cell aggregation **2.** Galapagos results for DA % & **3.** Middle floor DA% results for cell aggregated of the massing design



3.2 SERIES -2

Grid points were generated by subdividing the buildable area that represents the cell size, which were connected using interpolated curves that served as guides for massing. Four random section profiles, each with parametric height and length values, were projected onto the interpolated curves using the reference points. These sections were swept along the curves to generate a mesh. Using Ladybug and Honeybee, we evaluated this form to ensure that it minimises solar radiation while maximising natural daylight. Based on this optimised form, modular units were developed for the 1BHK, 2BHK, and 3BHK typologies. The Wasp plugin was used to set up the connection points and spatial rules for these modules, as shown in Fig. 6, and the overall process is shown in Fig. 7. These modules were arranged within the original mesh to ensure that the passive design principles were implemented. The generative process was re-run using the same environmental criteria and out of the various iterations, finally selecting the most efficient and environmentally responsive design.

Figure 5: The solar insolation generative design process for series 1



Site with setback and Open space

Central Rail curve

Generative solar incidental for the Rail curve

Generative location of 4 profile curves

Massing Mesh from profile curves on Rail curve

Massing Mesh Solar incidental analysis

Figure 6: Series -2: **1.** Grasshopper script, **2.** Generated form with cell aggregation of 3 typology of units & **3**. Arrangements of cell for 1BHK, 2BHK, and 3BHK typologies

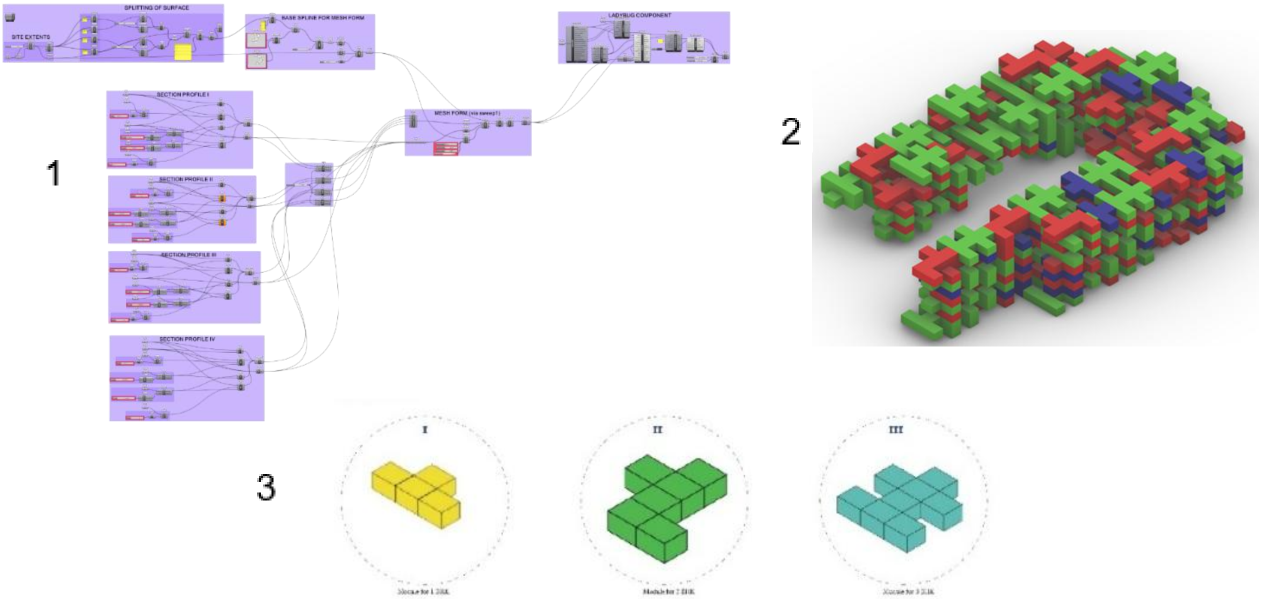
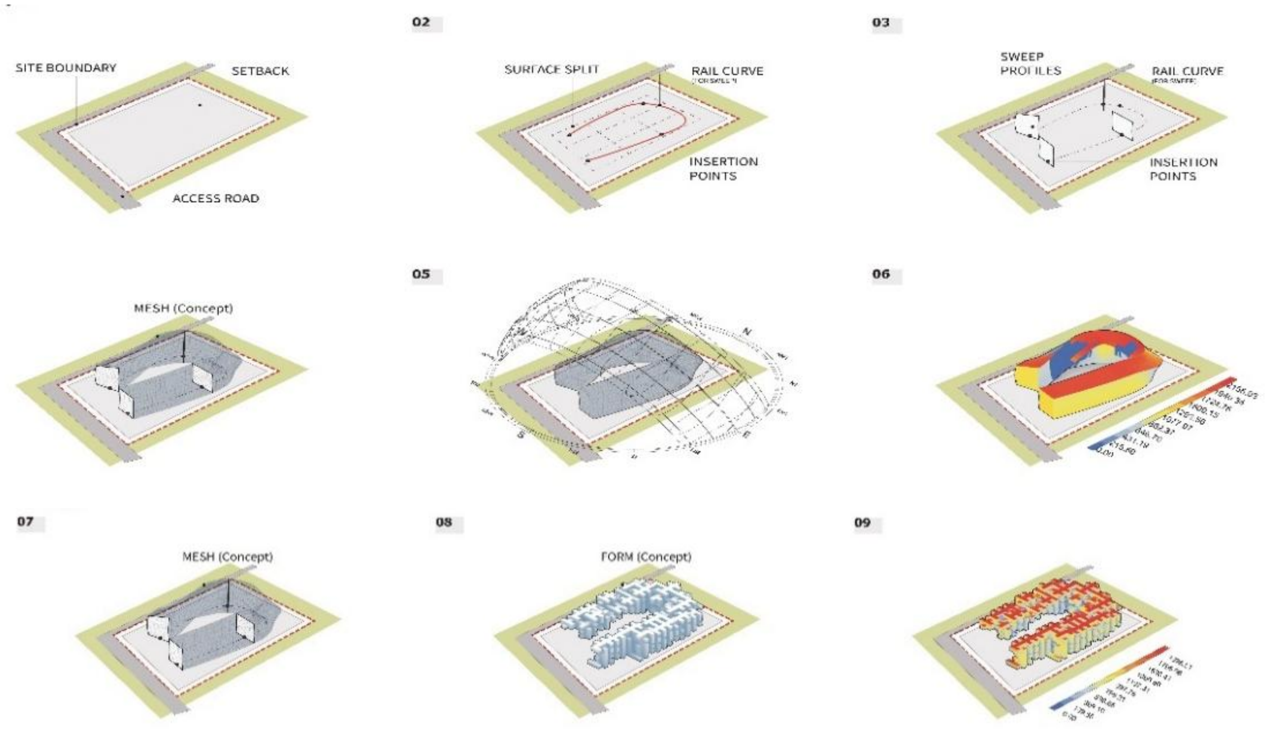


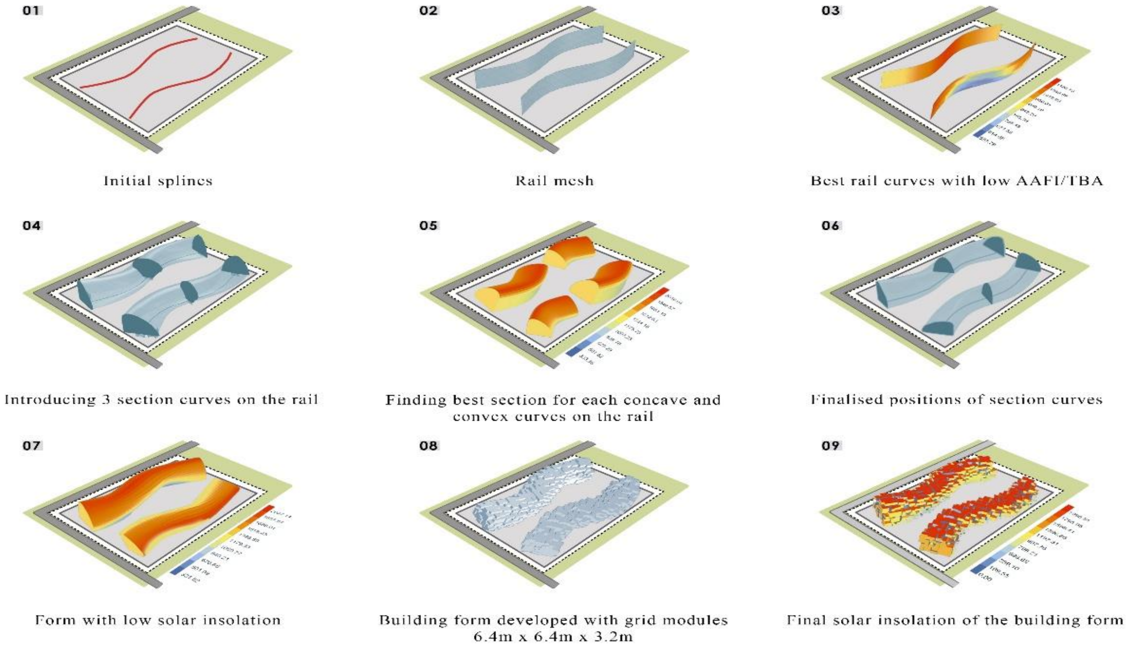
Figure 7: The solar insolation generative design process for series 1



3.3 Series -3

The initial concept involved a spline-based building form, hypothesizing that curvature could naturally aid in self-shading. Three-section curves were introduced to define the vertical profiles, and their positions along the main rail were again optimized using the genepool and Galapagos components for minimum solar insolation. Despite this, the form retained some hotspots. A further round of testing used concave and convex spline curves and different section profiles to optimize shading, the overall design process as in Fig 9 After selecting the most efficient configuration, a mesh sweep was created and 6.4m x 6.4m x 3.2m cell modules were placed to simulate room-level spaces 2 cells is 1 bedroom unit, 3 cells is 2-bedroom unit and 4 cell as 3-bedroom units. The resulting image of the generated form is shown in Fig. 9. The final form, now climatically responsive, was broken down into floor plates, from which floor plans were developed.

Figure 9: The Generative design process of solar insolation for series 3



4. Results and Discussion

The 3 experiments were tested for solar insolation and DA % the results as in Table 3.

Table 3: Results of solar insolation and DA% total average for all the floor

Series no	No of floors	TBA	AAFI/TBA W/m2	FA : TBA	SC	WWR %	Mean DA % for all the floors
1	7	38000	95	0.44	0.42	55	32.08
2	7	37540	69	0.37	0.36	48	48.2
3	7	39050	89	0.41	0.4	52	62.1

From the results, the street form in series 3 has a higher total built-up area (TBA) and best daylighting results, as most cells are oriented E–E-W orientation, but with more AAFI/TBA. Series 2 had the lowest solar insolation, as it avoided cell aggregation in the south, with the lowest ratio of façade area (FA) to TBA and Shading Coefficient with an optimal DA % of 48%. Series 1 had higher solar insolation, even with self-shaded cell aggregations and lower DA %.

Using this PBCA method, the resultant mass is efficient, and a variety of massing options are available in high-density mass housing. The massing design creates clear floor layouts which are structurally feasible, as they are based on uniform cell sizes, with double-loaded unit arrangements that could be customised as the user needs at the early design stage.

5. Conclusions

This study demonstrates the effectiveness of a performance-based cellular aggregation (PBCA) approach in optimizing solar and daylighting performance for high-density housing in hot and arid climates, such as Ahmedabad. By integrating environmental simulation with form generation during the early design phase, this method enables segmented customization, which is a limitation of this study. Among the typologies tested, the street form showed the best overall performance in terms of daylight access and buildable area, whereas the open court and court forms presented trade-offs between shading, facade efficiency, and thermal comfort. This approach not only supports sustainable design practices but also enhances the variety in mass housing design and structural clarity, with a focus on environmental performance. Future extensions of this method could promote user adaptability and mass customisation. This generative framework has broader applicability in similar climatic contexts across the Global South, contributing to resilient and liveable urban development in the future.

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COMPARISON OF PRECAST, VOLUMETRIC, AND 3D PRINTING TECHNOLOGY FOR EWS HOUSING

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ABSTRACT

Rapid urbanization and population growth in India have led to a significant housing shortage and need for faster and affordable construction, particularly for the Below Poverty Line (BPL), Economically Weaker Section (EWS), and Low-Income Group (LIG) populations. This research analyzes three emerging technologies (volumetric, precast, and 3D printing) and highlights the advantages of 3D printing technology in addressing the growing demand for affordable housing in the construction industry. This study compares various technologies in aspects such as construction time, cost, and manpower requirements. Case studies of 3D-printed buildings in India and Dubai are presented, highlighting significant reductions in construction time and labor costs. Despite the benefits of 3D printing technology, the study identifies that the technology is high-cost, limited by materials, and requires increased industry awareness. The paper compares existing housing schemes and suggests the most efficient design based on several criteria, while conducting a cost analysis to determine affordability for the targeted population. The paper concludes by emphasizing the importance of emerging technologies in the housing sector to improve construction efficiency and affordability, while addressing constraints in technology availability, raw material costs, and beneficiary participation. Recommendations for future research and development in 3D printing technology are provided, along with suggestions for making housing more affordable through the new technology, compact design, and public-private partnerships.

Keywords: EWS housing; Low-cost housing; New technologies; 3D printing; Housing schemes.

1. Introduction

Housing is crucial for economic, social, and civic development, and investing in housing drives economic progress (Jones, 2012). When communities face disasters, shelter becomes a top priority, second only to food and medical care. Quality housing contributes to wealth creation by appreciating, serving as a hedge against inflation, providing space for income-generating activities, and facilitating access to credit. According to the 2011 census, India's urban population was 377.10 million (31.16%), and it is projected to reach 1,200 million by 2025 and 1,800 million by 2050 (Gangani, M. G., et al., 2016). The country's urbanization rate increased from 27.81% to 31.16% between 2001 and 2011, according to the survey (Gangani, M. G., et al., 2016). The paper discusses the housing yearly demand-supply gap in Table 1.

Category	Annual Income (in Rs)	Affordability to pay EMI/rent (% of income)	Affordability to Pay cost of the house (Multiple of annual income)	Affordability EMI/Rent per month (in Rs.)	Affordable cost of the house (in Rs.)	Size of unit (Sq.ft)
BPL	90,000	5	4	375	3,60,000	320
EWS	3,00,000	20	4	5,000	12,00,000	320
LIG	3,00,000 - 6,00,000	30	4	15,000	24,00,000	650

Population growth, urbanization, rising incomes, insufficient affordable housing, and government policies drive housing demand (Agarwal et al., 2013; Gopalan & Venkataraman, 2015), while supply constraints relate to land affordability and financial and regulatory support. As defined by various housing policies, affordability depends on monthly household income, home cost, and dwelling unit size (MoHUA, 2015). EWS housing aims to provide secure and affordable housing to those in need, reducing poverty and improving living conditions. Technology adoption can meet this need efficiently, given rapid advancements in construction industry technology, which offer various benefits.

As indicated by the estimates from the Technical Group formed by the Ministry of Housing and Urban Poverty Alleviation (MHUPA), there is a housing deficit of 21.74 million for the EWS, 2.71 million for the LIG, and 0.24 million for the MIG & HIG, as detailed in Table 1 (MHUPA, 2011). Greater demand for housing in the EWS category, adopting new technologies that are cost-effective and enable quicker construction, could be advantageous, as their annual income level ranges from Rs. 90,000 to 6,00,000. The affordable cost of a house ranges from Rs. 3,60,000 – 24,00,000, the maximum unit size can be 320-650 sq. ft. as shown in Table 1.

Table 2: Affordability as per their income

Sr.no	Category	Shortage (in million)
1	EWS	21.74 (88%)
2	LIG	2.71 (11%)
3	MIG-HIG	0.24 (1%)
Total		24.71 (100%)

Font Adapted from Ministry of Housing and Urban Poverty Alleviation (2012)

The three main challenges to constructing affordable housing are obtaining clearances, and land acquisition, with costs and approvals being the top challenges (Jones, 2012). Developing affordable housing requires overcoming regulatory, administrative, and financial barriers. The shortage of suitable land for affordable housing is another major issue. Acquiring land for low-cost housing is costly and time-consuming, with an 18-month approval process followed by an 18-month construction period

[Rana, D. P., & Rana, A. K. 2016]. Simplifying the approval process could enable developers to build more affordable homes if the government reduces required approvals. These challenges highlight the need for better alternatives in housing construction to enhance speed and meet rising housing demand. This paper aims to identify the most efficient emerging construction technology to address this shortage for EWS and LIG populations in India. To achieve this, the study will conduct a comparative analysis of precast, volumetric, and 3D printing technologies based on cost, time, and labor efficiency. The findings from this analysis, supported by real-world case studies, will be evaluated against the affordability criteria of the target demographic and existing government housing schemes. Finally, the paper will discuss the implications of the findings and provide recommendations for policy and future adoption.

2. Methodology

This study employed a qualitative and comparative approach to evaluate the efficacy of emerging construction technologies for affordable EWS housing in India. The research was conducted in four sequential phases: (1) a technology screening and selection phase; (2) a comparative analysis phase; (3) a validation and contextualization phase; and (4) an assessment of the government scheme phase. This design was selected to allow an in-depth, multi-faceted evaluation of each technology's performance against the critical constraints of the Indian affordable housing sector.

An initial review of industry literature identified seven prevalent emerging technologies: sub-assembly and components, panelized systems, 3D volumetric MCM systems, semi-volumetric, pods, modular, and hybrid systems (Shibani, A., et al., 2021). From this list, three technologies were selected for detailed analysis: precast construction, volumetric modular construction, and 3D printing.

This selection was justified based on different aspects, such as High Potential for Scalability (All three are suited for large-scale project deployment), Relevance to EWS Design (They are compatible with the repetitive, standardized unit designs typical of EWS housing projects), Significant Documented Advantages (Each promises substantial improvements over conventional methods in areas like time, cost, or waste reduction), as established in preliminary literature reviews.

Data for the comparative analysis were systematically collected from a comprehensive review of peer-reviewed academic literature, published industry case studies, project reports, and cost databases. The data extraction focused on quantifiable metrics critical to affordable housing delivery, such as Construction Cost, Construction Time, and Labor Requirements.

This data was synthesized to create a comparative framework (Table 3). The technology demonstrating the highest efficiency gains—3D printing—was then subjected to further validation through analysis of specific real-world case studies. These case studies provided concrete evidence of the technology's application, benefits, and practical challenges.

To ground the technical findings in socioeconomic reality, a cost-benefit analysis was conducted. The total cost of constructing a standard 300-320 sq.ft EWS unit using the selected technology was calculated. This cost was then evaluated against the affordability parameters for the BPL, EWS, and LIG demographic (as defined in Table 2) and the subsidy frameworks available under the Pradhan Mantri Awas Yojana (PMAY) and its sub-schemes (CLSS, AHP, BLC, ISSR). This dual analysis ensured the findings were not only subjective but also economically and politically feasible within the current Indian context.

3. New technologies in housing:

The escalating housing demand in India, driven by rapid population growth and urbanization, creates a pressing need for more effective construction methods. In response, emerging technologies present a promising alternative to conventional practices, offering significant advantages such as reduced construction time and cost, as well as enhanced adaptability to diverse site conditions through material innovation. The construction industry is increasingly recognizing this potential. A survey indicates that 50% of professionals believe new technology is crucial to reducing the national housing shortage (Sheikh and Sharma, 2021). This demonstrates that adoption of these methods has concrete benefits. Projects utilizing modern techniques show marked improvements in energy efficiency, a reduced environmental footprint through minimized waste, and enhanced safety protocols with lower CO2 emissions (Maqbool et al., 2023; Shibani et al., 2021).

This new technology construction involves off-site design, approvals, infrastructure, foundation, and manufacturing. By using technology, many stages can be completed off-site, reducing on-site construction time. However, off-site design time can be higher, as minor mistakes can affect component fitting. Utility and labor costs are lower due to pre-design and mechanization. Maintenance costs decrease as components are built in preferred conditions off-site. Industry professionals acknowledge that technology has efficiency in reducing costs and resource usage. A survey showed industry professionals accept technology's efficiency in reducing costs and resource consumption (Sheikh and Sharma, 2021). Cumulatively, these benefits underscore the potential of emerging technologies to revolutionize construction efficiency and sustainability.

While technology adoption has benefits, initial machinery costs and transportation are barriers. Design flexibility can be limited by mass production, but it is less problematic in the housing sector. Poor integration due to limited knowledge poses challenges. Skill scarcity highlights the need for training programs.

Therefore, the construction industry must adopt new technologies to address the current need for housing shortage in India. This can be achieved by taking efficient steps, such as ensuring the availability of appropriate technology, skill development for laborers, and encouraging beneficiary participation in the building process. In this paper, the efficient technology for low-income households is analyzed, and the policy adoption of technology in the construction industry is discussed.

The most widely used technologies in the industry were identified as sub-assembly and components, panelized systems, 3D volumetric MCM systems, semi-volumetric, pods, modular, and hybrid [Shibani, A., et.al 2021]. From these, the consolidated technologies selected for further study were volumetric, precast, and 3D printing. Volumetric construction involves the use of factory-built units that are transported to the construction site and assembled. These modular units, known as "volumetric modules", can include entire rooms or parts of rooms and are built with a high level of customization to fit the specific requirements of a project. Volumetric construction can offer advantages such as faster construction times, reduced material waste, and higher levels of quality control.

Precast construction involves the manufacture of building components, such as walls, floors, and stairs, off-site in a factory or casting yard. These components are then transported to the construction site and assembled to form the building structure. Precast construction can offer advantages such as faster construction times, reduced material waste, and improved durability.

3D printing, also known as additive manufacturing, involves the use of computer-controlled machines to create three-dimensional objects by layering material on top of itself. 3D printing is used to construct building components, including walls, floors, and even entire buildings. 3D printing offers advantages such as reduced construction times, reduced material waste, and increased customization options.

Emerging technologies in the construction industry have been projected to be more efficient than conventional methods, particularly in terms of time consumption (Shibani et al., 2021; Priya & Neamitha, 2018).

A comparison of the project cost and time showed that these technologies were more efficient than the conventional method (Shibani et al., 2021), as summarized in Table 3. All of these technologies significantly reduced the manpower required for construction. The study compared BOQ and project management of various projects and considered the amount payable per square foot for each technology. The study also provides insights into the efficiency of emerging construction technologies in the housing sector, highlighting the potential for cost, time, and manpower savings, as well as improving construction quality.

4. Results: Comparative Analysis of Construction Technologies

To evaluate the efficiency of emerging technologies, an analysis was conducted using project data from the literature. The data on cost and time reduction for precast and volumetric construction were synthesized from findings reported by Shibani et al. (2021) and Priya & Neamitha (2018), who conducted comparative studies of modern and conventional methods. The data for 3D printing was derived from a combination of industry case studies, including the projects discussed later in this paper, and benchmarks established in the literature (Mehar et al., 2020; Yin et al., 2022). The metric of Rs./Sq. ft was calculated as the average of the cost ranges found in these studies, normalized to a comparable scale, and represents the estimated cost for deploying each technology in the Indian context for an EWS-type project.

The results of this comparative analysis are summarized in Table 3. The percentages indicate the average reduction in cost and time compared to a baseline of conventional construction methods, as established in the source studies.

Table 3: Comparative Analysis of Time and Cost for Precast, Volumetric, and 3D Printing (vs. Conventional Construction)

Technology	Percentage compared to conventional construction	Time	Rs. / Sq. ft
Precast	18 %	49 %	1189
Volumetric	20 %	50 %	1081
3D printing	30 %	95 %	916

Font Derived from Shibani et al. (2021), Priya & Neamitha (2018), and industry case analysis.

This precast construction will cost up to 1189/sq. ft. ft. 18% reduced in cost and 49%-time reduction compared to conventional construction. Then, the Volumetric construction will cost up to 1081/sq. ft. ft. 20% reduction in cost and 50% reduction in time compared to conventional construction. The 3D printing construction will cost up to 916/sq. ft. 30% reduction in cost and 95% reduction in time compared to the conventional construction, as shown in Table 3. The analysis indicates that while all three technologies offer significant improvements, 3D printing demonstrates the most profound efficiency gains, with a 30% reduction in cost and a 95% reduction in time. Consequently, 3D printing was identified as the most promising technology and selected for further investigation through specific case studies.

5. 3D printing

3D printing is a technology that is gaining popularity across various industries, including the construction sector. 3D concrete printing (3DCP) is an additive manufacturing process that uses a computer-controlled printer to deposit material layer by layer, gradually building up a three-dimensional structure (Mehar et al., 2020). The technology is based on digital modeling and can be broadly classified into three categories: contour crafting, D-shape, and concrete printing. The typical workflow involves several stages: digital modeling, segmentation of the model into printable instructions, the printing process itself, and necessary post-processing.

The printers themselves vary based on application. The most common types are 4-axis gantry printers, which operate within a fixed frame and are often used for manufacturing small components in a factory setting. For more flexible on-site applications, robotic arm (axis) printers are used for smaller structures, and large-scale crane printers are deployed to construct taller, full-scale buildings directly on location (Yin et al., 2022). Currently, it is possible to build up to 500 square feet of structure using a single printer.

The present obstacles that need to be addressed include the cost of 3D printing technology due to the initial investment for printers, and the lack of awareness and understanding within the industry about 3D printing technology and its applications. Currently, only a limited range of materials is used. Printers' capacity for using multiple materials to produce more complex structures is being experimented with. The large size of 3D printers makes it challenging and expensive to position them on-site. 3D printers can operate 24/7. There is a potential for disruption to the types of skills and labor required for designing and building homes [Priya, P.K., & Neamitha, M., 2018].

6. Validation Through Case Studies

To validate the potential of 3D printing identified in the comparative analysis, the following case studies of implemented projects were examined:

Case Study 1: In 2021, the first 3D printed house in India covered an area of 600 square feet as a single-storey building. The cost to construct the house using 3D printing technology was INR 5,50,000, whereas the cost using conventional methods was INR 8,11,330, resulting in an approximate difference of INR 2,61,330. The construction duration for the 3D printed house was only 4.5 days, while the conventional construction process took 150 days. This means that 97% of the time was saved using 3D printing technology.

Case Study 2: In 2023, utilized 3D printing technology to construct a two-story building (720 sq. ft.) on-site, providing structural support with horizontal and vertical rebar. This was the first G+1 building constructed using this technology. Using the 3D printing process, this building was finished in just 106 hours, a significant reduction in time compared to the 8 to 12 months required by traditional construction methods.

Case Study 3: The Dubai Municipality building was constructed using 3D printing technology and currently holds the record as the tallest 3D printed structure, with a height of 9.5 meters and an area of 6890 square feet. The building boasts intricate planning curves and complex shapes, and the entire construction process was carried out on-site using a gypsum-based mixture reinforced with traditional construction materials like a concrete foundation. The use of 3D printing technology reduced the required on-site labor to just three workers, resulting in a 60% reduction compared to traditional methods, and also led to a 30% cost reduction (Mehar, P., et.al.2020).

7. Schemes

Many subsidies are being proposed for the housing sector, especially for low-income people and EWS people (Karthikeyan et al., 2018). After studying about every scheme in India, the gap between schemes is vital to analyze. Non-assessment of housing, lack of transparency, project infrastructure, low quality, Etc. These issues are addressed in the Pradhan Mantri Awas Yojana (PMAY) (Karthikeyan et al., 2018). The Pradhan Mantri Awas Yojana (PMAY) is a government scheme launched by the Ministry of Housing and Urban Affairs (MoHUA) in 2015 to provide affordable housing to the economically weaker sections (EWS), low-income groups (LIG), and middle-income groups (MIG) in both rural and urban areas of India [Karthikeyan, V., et.al.2018].

PMAY has two components: Pradhan Mantri Awas Yojana-Urban (PMAY-U) and Pradhan Mantri Awas Yojana-Gramin (PMAY-G). PMAY-U is targeted towards providing affordable housing in urban areas, while PMAY-G is targeted towards rural areas. This program provides financial assistance to eligible individuals for the construction or purchase of a new home, or for the enhancement of an existing one.

According to the PMAY scheme, for economically weaker sections (EWS) and low-income groups (LIG), the carpet area of the house should not exceed 320 and 650 square feet. The PMAY scheme provides a subsidy on home loans only for the eligible beneficiaries based on their income category. The subsidy rates vary based on the beneficiary's income category and the loan amount. For EWS and LIG, the interest subsidy is 6.5% for a tenure of 20 years. To be eligible for the PMAY scheme, the beneficiary should not own a pucca house in their name or the name of any other family member, and should not have availed of any other central or state housing scheme (Gopalan, K., & Venkataraman, M., 2015).

8. Sub-schemes

Credit Linked Subsidy Scheme (CLSS) - purchase or construction of a house - subsidy amount ranges from 3% to 6.5% - up to Rs. 2.67 lakhs.

Affordable Housing in Partnership (AHP) - financial assistance to public and private entities for the development of affordable housing projects in partnership with beneficiaries. The scheme aims to provide housing to the urban poor through public-private partnerships (PPP) - up to Rs. 1.5 lakhs per house.

Beneficiary-Led Construction (BLC) - financial assistance for the construction of a house on their land or the land provided by the government. The beneficiaries are required to contribute a certain amount towards the construction of the house, while the government provides the remaining amount as financial assistance. Financial assistance provided under this scheme varies depending on the location and cost of the project. Generally, the financial assistance will be up to Rs. 1.2 lakhs.

In Situ Slum Redevelopment (ISSR) - basic amenities and housing to the slum dwellers by redeveloping the existing slum areas. The scheme provides financial assistance to the slum dwellers for the construction of pucca houses in place of the existing slums. Financial assistance provided under this scheme varies depending on the location and cost of the project. Generally, the financial assistance will be up to Rs. 1.5 lakhs.

9. Conclusion

This study identifies an efficient construction technology to mitigate India's acute affordable housing shortage. The comparative analysis revealed that 3D printing technology holds the greatest potential, demonstrating a 30% reduction in cost and a 95% reduction in time compared to conventional methods. The adoption of emerging technologies in the housing sector is crucial to address the increasing demand for affordable housing in India. These technologies improve construction speed and efficiency, reduce cost, and improve overall quality.

To construct a 320 sq. ft house, a cost of 3,00,000 is required, and even with the assistance provided by the government's housing schemes, the beneficiaries must contribute the remaining amount of 2,00,000. Most people can’t afford the whole amount, so they opt for the loan. If taken as a loan, the monthly payment would be Rs. 1065. If the interest is added, it may be affordable for the EWS and LIG, whose affordable EMI will be up to Rs. 5,000 and Rs. 15,000, but not for the BPL groups, whose affordability is a maximum of Rs. 375. To make housing more affordable, the cost should be reduced or the government subsidy should be increased. Ways to reduce the cost are by implementing efficient technology, reducing the area, and another option is to use AHP and PPP to lower the project cost for EWS individuals. By doing so, the house can become more affordable for those who need it.

However, some constraining factors must be considered, such as the unavailability of appropriate technology and low-cost raw materials, as well as the need for increased beneficiary participation in the building process. To overcome these constraints, efficient steps must be taken and made more accessible to the economically weaker sections of society. It is also important to address issues related to the availability and affordability of technology, as well as the need for responsive building technology institutions to cater to the specific requirements of the EWS housing sector. By addressing these constraints, the adoption of emerging technologies in the housing sector can pave the way for more efficient and effective construction methods, ultimately helping to alleviate the housing shortage in India.

10. Final Considerations

Companies are currently engaged in enhancing 3D printing technology, which could lead to the possibility of constructing multistorey buildings through further research and development.

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EXPLORING THE IMPACT OF WINDOW DESIGN ON THERMAL COMFORT AND OCCUPANT SATISFACTION IN A RESIDENTIAL HIGH-RISE BUILDING IN ABU DHABI, UAE

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ABSTRACT

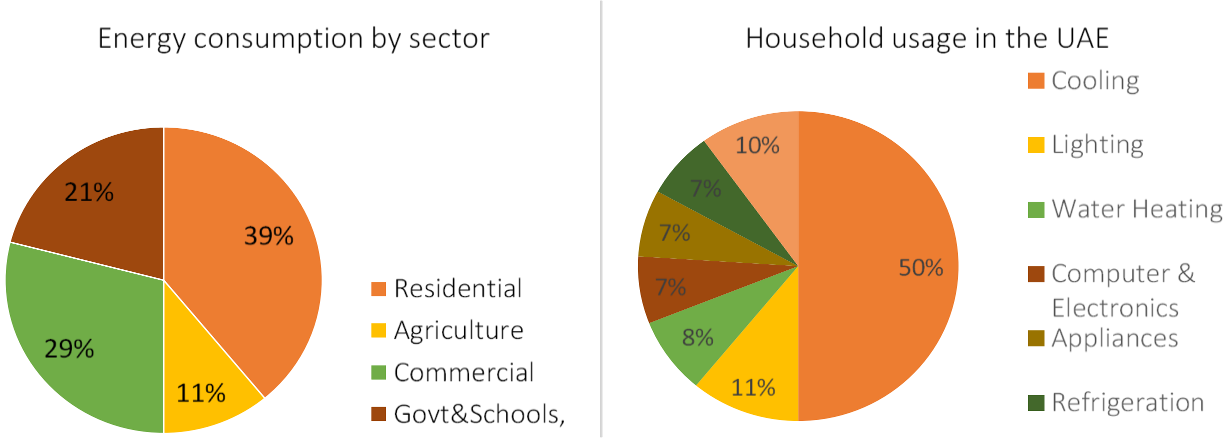
Thermal comfort (TC) is a key component of indoor environmental quality, influencing health, satisfaction, and productivity. In hot, arid regions like Abu Dhabi, extreme conditions make achieving TC a significant design challenge. High-rise residential buildings are typically built with fixed, non-operable windows, relying solely on mechanical HVAC systems. While these provide baseline temperature control, they remove natural ventilation and restrict user adaptability, raising concerns about humidity, air quality, and long-term well-being. This study examines the impact of fixed window design on TC and occupant satisfaction in an Abu Dhabi residential tower. It focuses on how the absence of operable windows limits ventilation, increases discomfort due to humidity, and reduces perceived control. Findings show that most residents were generally satisfied with the temperature and air quality, but dissatisfied with the humidity and stagnant air, which is directly linked to sealed windows. Many emphasized the importance of airflow, associating a lack of ventilation with discomfort and various health issues. Survey results indicated 81% believed fixed windows reduced TC, while 73% noted negative effects on well-being. The study highlights operable windows and hybrid ventilation as crucial for sustainable design, offering evidence-based insights for architects and policymakers. Ultimately, integrating natural ventilation is crucial for achieving long-term comfort, health, and satisfaction in hot, arid high-rises.

Keywords: Thermal Comfort (TC), Occupants' Satisfaction, Architectural Design, Operable Windows, Residential Buildings.

1. Introduction

Modern global development has significantly increased energy consumption in the building sector, with about one-third of fossil fuels now consumed by buildings. This surge is attributed mainly to the widespread adoption of mechanical systems for maintaining a comfortable indoor environment. Fig.1 shows the UAE's energy consumption by sector and household usage (Dubai Electricity and Water Authority, 2020). Thermal comfort, the state of mind that reflects satisfaction with the thermal environment, is influenced by various cultural, environmental, and personal factors (ASHRAE, 2017). Research on thermal comfort has evolved through two main approaches: climate chamber tests and field studies. Climate chamber tests have developed steady-state laboratory thermo-physiological models and standards, such as ASHRAE 55-1992 and ISO7730. In contrast, field studies have developed adaptive thermal comfort models and standards, including ASHRAE 55-2010, EN15251, and the Dutch ATG guideline (ASHRAE, 2017). These standards are now widely used in both research and practical applications. This study aims to assess a high-rise residential building in Abu Dhabi by examining the impact of architectural design choices on thermal comfort and occupant satisfaction. This research investigates the impact of these design choices on thermal comfort and overall satisfaction, providing insights into the relationship between architectural design and occupant well-being.

Figure 1: Energy consumption by sector and household usage in the UAE [1].



The architectural design of the selected high-rise residential building on Al Reem Island, Abu Dhabi, serves as the primary case study for this research (Hilal et al., 2023). This modern tower, approximately 300 meters tall, accommodates over 1,000 residents and features fixed, non-operable windows across all units. The building's reliance on centralized HVAC systems, without any natural ventilation openings, typifies a growing trend in high-rise residential design across the UAE. This design eliminates user control over airflow, restricts adaptive comfort strategies, and raises concerns regarding thermal comfort and indoor environmental quality (IEQ). The absence of operable windows has potential implications for indoor air quality, thermal conditions, and the health and well-being of occupants. Understanding these impacts is crucial for making informed decisions about building design to enhance IEQ and occupant satisfaction. Accordingly, this study explores the question: How does the absence of operable windows and reliance on air conditioning and mechanical ventilation impact thermal comfort and occupant satisfaction in the selected high-rise residential building in Abu Dhabi?

This research aims to enhance thermal comfort and occupant satisfaction in residential buildings that rely on mechanical ventilation and air conditioning. The objectives are:

a) To assess overall occupant satisfaction, focusing on thermal comfort within Indoor Environmental Quality (IEQ), b) To identify challenges and opportunities associated with residential building designs that heavily rely on mechanical ventilation and air conditioning. c) To assess the specific impact of the building's design on indoor environmental quality (IEQ) and occupant satisfaction. d) To provide guidelines for architects, planners, developers, and decision-makers to improve IEQ and thermal comfort in similar residential buildings.

A literature review reveals that numerous studies have explored strategies for achieving thermal comfort in high-rise residential buildings. These studies often emphasize the crucial role of building design, mechanical ventilation, and air conditioning systems in ensuring occupant comfort, particularly in hot climates. However, while these studies provide valuable insights, few explicitly examine how the absence of operable windows and the resulting lack of natural ventilation and user control impact occupant satisfaction and thermal comfort. This research bridges that gap by focusing on the fixed-window design as a critical architectural feature that restricts adaptive comfort strategies and contributes to long-term discomfort in sealed high-rise buildings. This research builds on those findings by examining thermal comfort and occupant satisfaction in residential buildings that depend heavily on mechanical ventilation and air conditioning. In doing so, it aligns with the study's objectives: assessing occupant satisfaction within the context of IEQ, identifying design-related challenges and opportunities, evaluating the influence of building design on IEQ, and ultimately offering design guidelines to enhance thermal comfort and ventilation strategies in similar settings. Indoor Environmental Quality (IEQ) encompasses several factors, including air quality, thermal comfort, lighting, acoustics, and spatial layout (Chen et al., 2020). Effective ventilation systems are crucial in managing these factors to create a satisfactory microclimate, which significantly impacts the comfort and well-being of occupants. With modern lifestyles keeping people indoors for over 85% of their time, maintaining high IEQ standards in various environments is crucial (Chen et al., 2020). Energy-saving practices introduced since the 1970s have enhanced thermal comfort by improving insulation and advancing HVAC systems (Awbi, 2003). However, these advancements have sometimes compromised indoor air quality, particularly in air-conditioned buildings, leading to issues like 'sick building syndrome' due to poor HVAC maintenance, high indoor pollutants, and insufficient outdoor air supply (Kamaruzzaman et al., 2018).

Noise from external sources such as traffic and mechanical systems can impact occupant well-being by causing irritability and distraction. Lighting, whether natural or artificial, is another critical aspect of IEQ, as natural daylight enhances light quality but can also potentially cause glare and thermal gain. Windows are vital for natural ventilation and daylight, playing a significant role in IEQ (Kamaruzzaman et al., 2018). Effective ventilation removes odors and toxins, as temperature, humidity, and air movement directly impact occupant productivity and comfort. Architectural decisions regarding layout, materials, and fenestration have a significant impact on natural light, ventilation, thermal comfort, and indoor air quality, ultimately affecting the overall indoor environment (Muhamad Salleh et al., 2015), Parkinson, Parkinson & Dear, 2019).

Thermal comfort in indoor environments is typically assessed using standards such as ASHRAE Standard 55 (ASHRAE, 2017) and ISO 7730 (ISO, 2005), which employ heat-balance methods, including the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) (Parkinson, Parkinson & Dear, 2019). These standards define the acceptable thermal comfort levels, taking into account factors such as metabolic rate and clothing insulation. In residential buildings, thermal comfort varies with activities, seasons, and adaptive behaviors (ISO, 2005). For instance, summer bedroom temperatures for comfort range from 26.4°C to 27.5°C, while the recommended winter minimum neutral temperature is 16°C. Bathrooms require temperatures between 24°C and 28°C for optimal comfort during activities such as showering (Peeters et al., 2009). Adaptive measures, such as opening windows, adjusting clothing, and using fans, are essential for maintaining comfort in various residential spaces.

2. Methodology

This study adopted a mixed-methods research design to comprehensively investigate the impact of window operability on thermal comfort and occupant satisfaction in a high-rise residential building located on Al Reem Island, Abu Dhabi. The mixed-methods approach was chosen to integrate the strengths of quantitative measurement and qualitative interpretation, thereby enhancing the validity of findings through data triangulation (Creswell, 2003). A convergent-parallel design was employed, wherein quantitative and qualitative data were collected simultaneously, analyzed independently, and then integrated to provide a holistic understanding of the research problem.

2.1 Sampling and Participants

The research targeted occupants of a residential tower characterized by fixed, non-operable windows and exclusive reliance on mechanical ventilation. A random sample of 100 residents participated in the quantitative survey, while ten residents were purposively selected for in-depth semi-structured interviews. Participants represented diverse age groups, occupations, and apartment types, ensuring demographic and spatial representation. Before participation, all respondents were briefed on the study objectives and provided written informed consent in compliance with the ethical protocol of the United Arab Emirates University.

2.2 Data Collection

The quantitative survey, designed in accordance with ASHRAE Standard 55 (2017) (ASHRAE, 2017), and ISO 7730 (ISO, 2005), assessed critical parameters influencing thermal comfort, namely indoor temperature, humidity, ventilation adequacy, and perceived air quality. Responses were captured using a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The qualitative component comprised face-to-face semi-structured interviews exploring occupants' perceptions of thermal comfort, air freshness, humidity levels, and user control.

All interviews were audio-recorded, transcribed verbatim, and supplemented by field observations and review of architectural documentation, including HVAC drawings and façade details.

A concise comparative summary of both data-collection phases, instruments, and analytical techniques is presented in Table 1.

Table 3: Summary of Research Design and Data Collection Framework

Component	Quantitative Phase	Qualitative Phase
Purpose	Measure occupants' satisfaction and perceptions of thermal comfort and Indoor Environmental Quality (IEQ).	Explore residents' experiences, adaptive behaviors, and perceived comfort in sealed environments.
Sample Size	100 residents (random sampling)	10 residents (purposive sampling)
Instrument	Structured online questionnaire (5-point Likert scale)	Semi-structured interview guide (open-ended questions)

Key Parameters	Temperature comfort, humidity, ventilation, air quality, satisfaction with window design	Comfort experience, air freshness, humidity perception, perceived control, health and well-being
Collection Method	Online survey via a secure platform	Face-to-face interviews (30–45 min each) + site observation
Standard References	ASHRAE 55 (2017); ISO 7730 (2005)	Braun & Clarke (2006) thematic analysis framework [12]
Data Analysis Tools	SPSS 27 (descriptive and correlation analysis)	Manual coding and theme generation
Output	Quantified satisfaction levels and statistical relationships	Emergent themes explaining user experience and comfort perceptions

2.3 Data Analysis and Ethical Considerations

Quantitative data were analyzed using SPSS Version 27, employing descriptive statistics to summarize occupant responses and Pearson's correlation analysis to explore associations among thermal-comfort variables. Qualitative data were processed using thematic analysis following Braun and Clarke (2006), a six-phase approach: familiarization, coding, theme identification, review, definition, and synthesis. Integration of both datasets during interpretation allowed methodological triangulation, strengthening the internal validity and depth of the findings. Ethical approval was obtained from the Institutional Review Board (IRB) of the United Arab Emirates University, and all procedures complied with research ethics guidelines concerning anonymity, informed consent, and data confidentiality.

2.4 Case Study Description

The selected high-rise residential building is located on **Al Reem Island, Abu Dhabi**, and exemplifies contemporary architectural design characterized by fully sealed façades and reliance on mechanical air conditioning. The tower, approximately **300 meters in height**, accommodates over **1,000 residents** and is constructed primarily of glass, steel, and concrete. The design employs **fixed, non-operable windows**, which eliminate natural ventilation pathways and limit occupant control over airflow. Although the building offers modern amenities and aesthetic appeal, this configuration presents challenges for maintaining adequate **Indoor Environmental Quality (IEQ)**, particularly concerning humidity regulation and air freshness.

The study therefore investigates how this design typology influences occupants' perceptions of thermal comfort, satisfaction, and well-being, aiming to inform future architectural practices and policy interventions that improve high-rise living conditions in hot, arid regions.

3. Results and Discussion

This section presents both the quantitative and qualitative findings, integrating statistical analysis with residents' experiential insights. Results are discussed in relation to ASHRAE Standard 55 and ISO 7730 (2005).

3.1 Quantitative Results

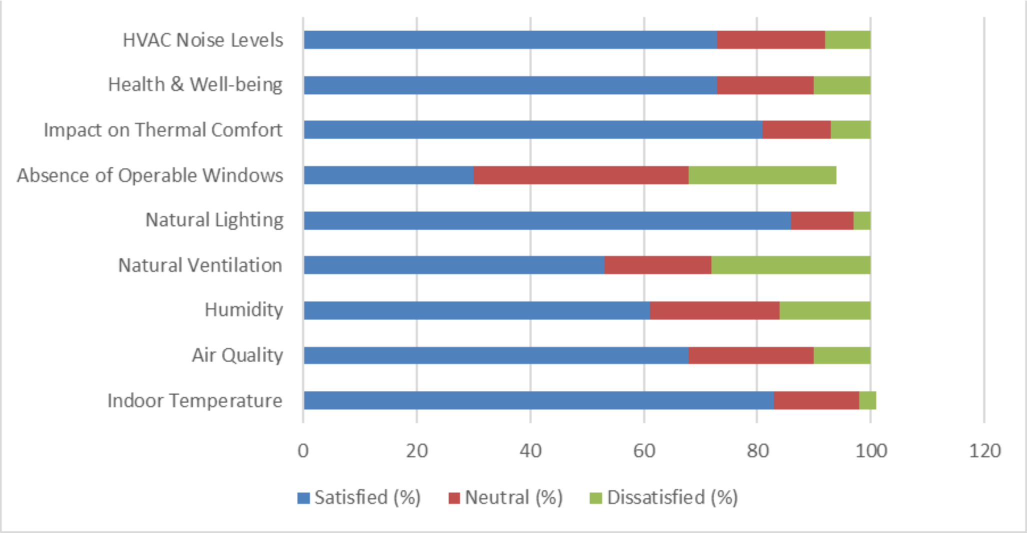
The quantitative analysis comprised two main components: (a) a review of official building documents obtained from Abu Dhabi Municipality, including drawings and specifications of HVAC systems and façade design, and (b) an online survey distributed to 100 residents. The survey captured occupants' perceptions of thermal comfort and IEQ parameters such as indoor temperature, humidity, ventilation, lighting, and satisfaction with window design. Table 2 summarizes the main quantitative findings from the survey.

Table 4: Summary of Occupant Responses to Key Thermal Comfort Indicators (n = 100).

Parameter	Satisfied (participants)	Neutral (participants)	Dissatisfied (participants)	Key Interpretation
Indoor Temperature	83	15	3	Overall satisfaction with indoor temperature, consistent HVAC performance.
Air Quality	68	22	10	Moderate satisfaction; perceived stagnation in some units.
Humidity Control	61	23	16	Need for enhanced dehumidification, especially in sealed rooms.
Natural Ventilation	53	19	28	Limited satisfaction due to the absence of operable windows.
Natural Lighting	86	11	3	High satisfaction; daylight penetration is effective.
Absence of Operable Windows	30	38	26	Mixed responses; desire for controllable airflow.
Impact on Thermal Comfort	81	12	7	Strong correlation between lack of window operability and discomfort.
Health & Well-being Effects	73	17	10	Occupants link poor ventilation to health issues.
HVAC Noise Levels	73	19	8	Generally satisfactory acoustic environment.

As shown in Figure 2, the most critical concern among respondents was the lack of natural ventilation, cited by 81% as directly affecting comfort and 73% as influencing overall well-being. These findings underscore the dependence of thermal satisfaction on opportunities for adaptive control, such as operable windows and airflow regulation, which are absent in this case. Respondents demonstrated a clear differentiation between temperature control, which was widely satisfactory, and air movement and humidity, which were reported as deficient. This aligns with the adaptive comfort previous study (Yousefi et al., 2017), suggesting that static HVAC systems may ensure thermal neutrality but not necessarily perceived comfort.

Figure 2: Occupant Responses to Key Thermal Comfort Indicators



3.2 Qualitative Findings

The qualitative analysis, based on ten in-depth interviews and on-site observations, provided deeper insight into residents' lived experiences. Thematic analysis identified five dominant themes:

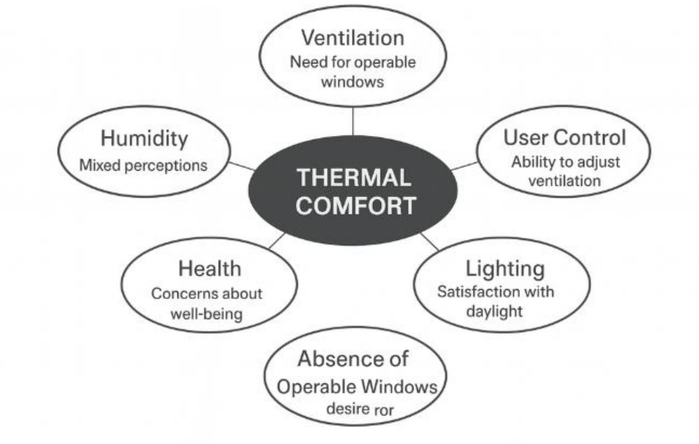
1. Comfort with Indoor Temperature and Air Quality:
2. Most participants reported general satisfaction with indoor temperature and perceived air cleanliness. However, a recurring observation was that air often felt "stale" or "lacking freshness," attributed to sealed façades and low air exchange rates.
3. Mixed Perceptions of Humidity and Ventilation:
4. Some occupants expressed satisfaction with humidity levels, while others reported discomfort during humid months, noting condensation on glass façades and difficulty breathing in tightly sealed spaces.
5. Need for Operable Windows:
6. The absence of operable windows was the most frequently mentioned issue. Participants emphasized psychological discomfort due to their inability to open windows, even for short periods, reinforcing the link between control and comfort.
7. Health and Well-being Concerns:
8. Over 60% of interviewees mentioned health-related symptoms, including mild respiratory irritation, fatigue, and allergies, which they linked to insufficient ventilation and continuous HVAC usage.
9. Positive Views on Natural Lighting and Acoustic Comfort:

Residents expressed high satisfaction with natural lighting levels and reported minimal disturbance from HVAC noise, suggesting that glazing design effectively balances illumination and acoustic isolation.

A visual synthesis of these themes is presented in Figure 3, illustrating the interrelation between environmental parameters and occupant perceptions.

The convergence of quantitative and qualitative data shows a clear pattern: the absence of natural ventilation is the main factor reducing thermal comfort. This finding aligns with results from studies in similar climates (Kamaruzzaman et al., 2014; Al-Horr et al, 2016), which highlight the physiological and psychological benefits of occupant-controlled ventilation.

Figure 3: Thematic Framework of Qualitative Findings.



3.3 Integrated Discussion

The integration of both data sets reinforces three key insights:

1. Thermal Comfort vs. Perceived Freshness:

While temperature levels meet ASHRAE and ISO standards, the perceived air freshness remains inadequate without operable openings, underscoring the limitation of purely mechanical ventilation systems.

2. User Control and Psychological Satisfaction:

Occupants equate comfort not only with environmental conditions but also with the ability to adjust them, a principle central to adaptive comfort models.

3. Design Implications for High-Rise Buildings:

The evidence supports integrating hybrid ventilation strategies, operable façade elements, and intelligent environmental controls in high-rise design, particularly in hot-arid climates like Abu Dhabi. These interventions can improve perceived comfort, mitigate health risks, and enhance overall IEQ.

4. Conclusion

This study investigated the impact of window operability on thermal comfort and occupant satisfaction in a high-rise residential building in Abu Dhabi using a convergent mixed-methods design. The integration of quantitative survey results and qualitative interview findings provided a holistic understanding of indoor environmental quality (IEQ) under fully mechanical ventilation conditions. The results revealed that while occupants generally expressed satisfaction with indoor temperature and natural lighting, they reported discomfort associated with limited air movement, humidity variation, and the absence of operable windows. These findings underscore the critical importance of natural ventilation and user control in achieving overall comfort and well-being in sealed high-rise buildings.

The absence of operable windows was identified as a significant limitation affecting both perceived air freshness and psychological comfort. Approximately 81% of respondents indicated that the lack of window operability directly influenced their thermal comfort, while 73% associated this constraint with negative effects on well-being. Qualitative findings reinforced these results, highlighting the desire for increased personal control and adaptive behaviors, core principles of the adaptive thermal comfort model. The outcomes confirm that mechanical systems alone, though capable of maintaining thermal neutrality, do not fully satisfy the complex comfort needs of occupants in hot-arid climates.

The study contributes to the practical understanding of ASHRAE Standard 55 and ISO 7730, emphasizing that occupant satisfaction depends not only on measurable environmental parameters but also on the ability to adapt to changing indoor conditions. Future design strategies for high-rise residential buildings in the UAE and similar climates should consider integrating hybrid ventilation systems, operable façade components, and intelligent environmental controls to enhance comfort, health, and energy efficiency. By linking design variables with occupant perceptions, this research provides evidence-based recommendations for architects, developers, and policymakers striving to create healthier, more adaptive, and sustainable indoor environments.

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CHAPTER 5

STRATEGIES FOR HOUSING WITH REDUCED CARBON FOOTPRINT

ADVANCING LOW-CARBON MODULAR HOUSING: A COMPARATIVE ASSESSMENT OF BIO-BASEDTHERMAL INSULATION IN WIKIHOUSE SYSTEMS FOR HIGHLAND CLIMATES

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ABSTRACT

This study evaluates the thermal performance of a modular housing prototype based on the Wikihouse Skylark 250 system for high-altitude Andean climates, integrating bio-based insulation materials. The objective was to assess the feasibility of combining digital fabrication with low-impact materials to enhance passive thermal comfort. Three insulation scenarios were tested, rice husk fiber, wheat straw fiber, and recycled polyurethane foam (PUR), using steady-state hygrothermal analysis (Ubakus) and dynamic simulation DesignBuilder v5.5 Measured thermal conductivities were 0.040 W/m·K (127 kg/m^3) for rice husk, 0.034 W/m·K (80 kg/m^3) for wheat straw, and 0.050 W/m·K (30 kg/m^3) for PUR. U-values ranged from 0.34 W/m^{2}K (wheat straw) to 0.48 W/m^{2}K (PUR), compared to 1.35 W/m^{2}K for the uninsulated case. Time lag improved from 2.5 h (uninsulated) to 14.5 h (wheat straw. Dynamic simulations without HVAC showed that bio-based insulation increased winter indoor temperatures by up to 6 °C over the uninsulated wall, maintaining conditions within or near the 19–25 °C comfort range most of the year. Results demonstrate that integrating natural insulation into modular systems can provide low-energy, climate-adapted housing solutions for the Peruvian highlands, ensuring indoor comfort through passive strategies without reliance on active HVAC systems.

Keywords: Modular construction; Bio-based insulation; High-altitude housing; Thermal simulation; Passive design.

1. Introduction

The construction sector accounts for nearly 40% of global energy use and around 36% of CO_2 emissions (IEA, 2023). In cold highland climates such as the Andean regions above 3500 m.a.s.l., heating demand is high, often worsened by inadequate insulation in self-built rural and peri-urban housing, leading to energy poverty (Deutsche Gesellschaft für Internationale Zusammenarbeit [GIZ], 2013)

Modular construction offers scalability, precision, and material efficiency. The Wikihouse system, an open-source, CNC-fabricated plywood platform, enables local manufacturing and rapid assembly (Sajid, Ullah, Qayyum, & Masood, 2024). While its structural advantages are well documented, its thermal performance in extreme climates, particularly with alternative insulation strategies, remains underexplored.

The valorization of agricultural residues aligns with circular economy and low-carbon goals. Bio-based insulations such as rice husk (Rodríguez Neira et al., 2025) and wheat straw fibers are abundant, renewable, and exhibit promising thermal properties (Asdrubali et al., 2015; Buratti et al., 2021), offering viable alternatives to conventional insulators (Papadopoulos & Giama, 2007).

This study analyzes a Wikihouse-based modular wall system adapted for high-altitude climates. Through dynamic energy simulation and steady-state hygrothermal analysis, it assesses the feasibility of integrating bio-based insulation into low-impact modular housing for the Peruvian highlands, as part of broader research combining digital modular systems with natural materials and vernacular principles, such as the use of *sillar* (ignimbrite) in Andean construction, which has demonstrated notable thermal performance and reinforces the value of local resources in sustainable design (Herrera-Sosa et al., 2020).

2. Materials and methods

2.1 Prototype Configuration

The modular prototype was developed using the Wikihouse system, specifically the Skylark 250 version, which follows a digitally fabricated, open-source construction logic. The structural components were modeled in SketchUp and Fusion 360, and fabricated using a 3-axis CNC router from 18 mm-thick plywood panels. The assembled module was previously constructed and serves in this study as the basis for assessing various insulation strategies under high-altitude climatic conditions (Romero Quidel et al., 2023). As shown in Figure 1, the prefabricated unit integrates structure and envelope in a lightweight system. Its 250 mm wall cavity, characteristic of the Skylark design, was filled via blow-in technique with the insulation materials tested. High-efficiency glazing was incorporated, enabling a rapid-assembly solution optimized for cold-climate housing in the Andean highlands.

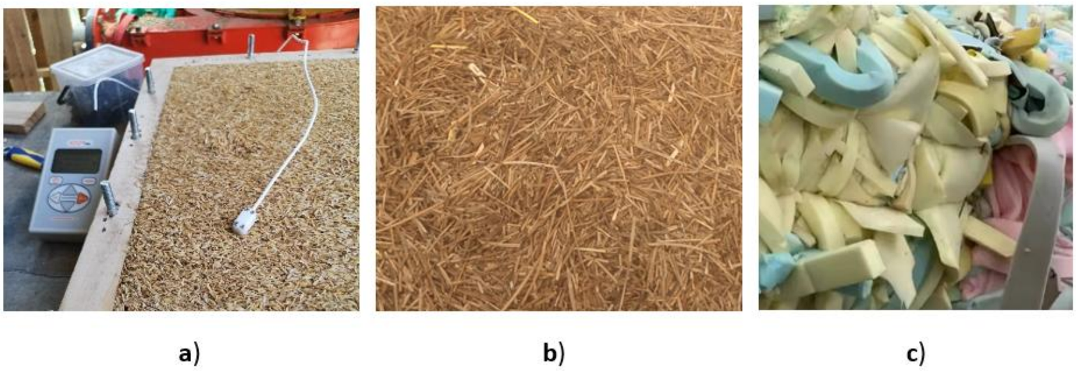
Figure 1: Wikihouse modular prototype and insulated wall section with rice husk infill.

2.2 Insulation materials and thermal properties

To evaluate the thermal performance of different insulating strategies within the modular wall system, three materials were selected: rice husk fiber, wheat straw fiber, and recycled polyurethane foam (PUR). The two natural fibers are agricultural residues widely available in Peru, while PUR was selected as a conventional benchmark for comparison. (Rodríguez Neira et al., 2024; Rojas-Herrera et al., 2023)

The thermal conductivity of the insulation materials was measured using the *KD2 Pro* thermal properties analyzer. This portable device, compliant with IEEE 442–1981 and ASTM D5334-08 standards, employs an interchangeable needle sensor that is inserted into the material. Each measurement cycle consists of a 90-second heating and cooling period, with data recorded at one-second intervals. For each material, three specimens of loose-fill insulation were prepared, and four internal points were measured per specimen to ensure consistency and accuracy. (Figure 2). This method was applied to characterize the thermal behavior of rice husk fiber, wheat straw fiber, and recycled polyurethane foam, all intended for blow-in application in the modular wall cavity.

Figure 2: Tested insulation materials: (a) rice husk fiber during thermal conductivity measurement with KD2 Pro; (b) wheat straw fiber; (c) recycled polyurethane foam.

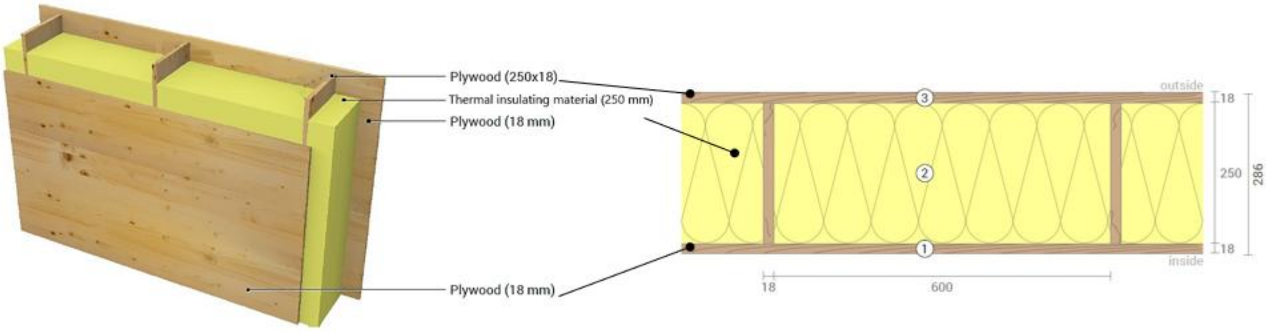


2.3 Hygrothermal assessment with Ubakus

The hygrothermal behavior of each wall configuration was assessed in Ubakus, following ISO 6946 for multi-layered envelopes. Simulations represented Peruvian highland conditions (>3,500 m.a.s.l.) with external values of –2 °C and 60% RH, and internal conditions of 20 °C and 50% RH.

Four wall assemblies were evaluated: three with insulation (rice husk, wheat straw, recycled polyurethane) and one uninsulated. Performance indicators included thermal transmittance (U-value), time lag, decrement factor, and heat storage capacity. The analyzed system, shown in Figure 3, features a 250 mm core cavity framed by 18 mm plywood, allowing flexible infill with different insulation materials.

Figure 3: Modular wall configuration simulated in Ubakus: exploded view and vertical section.



2.4 Dynamic simulation in DesignBuilder

The dynamic thermal performance of the modular prototype was simulated in DesignBuilder for a temperate highland climate with dry winters (Köppen–Geiger: Cwb), representative of the southern Peruvian Andes above 3,500 m.a.s.l. This climate is characterized by moderate summer temperatures, colder winters, and low precipitation during the cold season. No active HVAC systems were included, enabling the assessment of passive thermal behavior. The simulation parameters are detailed in Table 1.

Four scenarios were modeled: rice husk fiber, wheat straw fiber, recycled PUR, and no insulation. The simulation was used to estimate the monthly indoor air temperature within the modular prototype under passive conditions, considering the effect of each insulation material. This approach allowed the identification of indoor temperature trends and the thermal stability provided by each configuration throughout the year, supporting a comparative assessment of their passive performance potential in high-altitude climates.

Table 1: Parameters for Energy Simulation in DesignBuilder

Parameters	Characteristics
Activity	0.02 (people/m^2)—residential, residential occ schedule
Construction	Walls, roofs, and floors of Skylar 250 system have model infiltration of 0.7 (ac/h)
Opening	30% wall to window ratio—double glazing, clear, 6mm/6mm
Lighting energy	5.0 /m^2—100 lux

3. Results

3.1 Prototype Configuration

The Wikihouse modular system, developed using the Skylark 250 "M block" configuration, served as the reference prototype for this study. Although originally constructed as part of a previous implementation, the system was selected due to its structural efficiency, digital fabrication logic, and suitability for passive design strategies in cold high-altitude regions.

Each wall component was CNC-milled from 18 mm-thick plywood sheets using a parametric design that allowed two “M” block pieces to be obtained per sheet. A total of 34 plywood boards were required to complete the entire set of wall components for the prototype. The interlocking mechanism of the system enables fast and precise assembly without adhesives or mechanical fasteners, while its parametric nature allows for flexible adjustments in geometry—such as repositioning of openings—without compromising structural integrity.

Some limitations were observed during the milling process: to ensure precision and effective interlocking, the plywood boards must be in optimal physical condition. Warping, surface defects, or humidity-induced deformations can negatively affect assembly tolerances. Nonetheless, the system proved to be a flexible and replicable platform for testing thermal performance enhancements through natural insulation strategies, particularly suited for deployment in rural and peri-urban highland contexts

3.2 Insulation materials and thermal properties

The thermal conductivity and density of the three insulation materials tested are summarized in Table 2. The rice husk fiber exhibited a conductivity of 0.040 W/m·K and a bulk density of 127 kg/m^3, while wheat straw fiber showed slightly better insulating performance with a conductivity of 0.034 W/m·K and a lower density of 80 kg/m^3. In contrast, recycled polyurethane foam (PUR), although commonly used in industrial applications, presented a conductivity of 0.050 W/m·K and a significantly lower density of 30 kg/m^3.

Table 2: Thermal conductivity and density results of the insulation material tested

Material	Thermal Conductivity W/m·K	Density kg/m^3
Rice husk fiber	0.04	127
Wheat straw	0.034	80
Recycled PUR	0.05	30

Beyond thermal resistance, the practical applicability of bio-based fibers is influenced by their hygrothermal and environmental behavior. Rice husk and wheat straw, due to their open porosity, allow moisture transfer through vapor pressure gradients and capillary action; however, vapor diffusion remains the dominant mechanism in well-designed walls, helping control humidity and preserve insulation performance (Mehrez, Hachem, & Jemni, 2022). From a life-cycle perspective, these fibers also show considerably lower embodied energy than recycled PUR, which, despite valorizing industrial waste, still presents higher energy demand and greenhouse gas emissions (Papadopoulos & Giama, 2007).

The measured properties serve as a basis for the dynamic simulation and hygrothermal analysis presented in the following sections.

3.3 Hygrothermal assessment with ubakus

The hygrothermal analysis performed with Ubakus revealed significant differences in thermal performance among the four wall configurations evaluated. As shown in Table 3, the inclusion of bio-based insulation materials markedly improved the thermal behavior compared to the uninsulated wall.

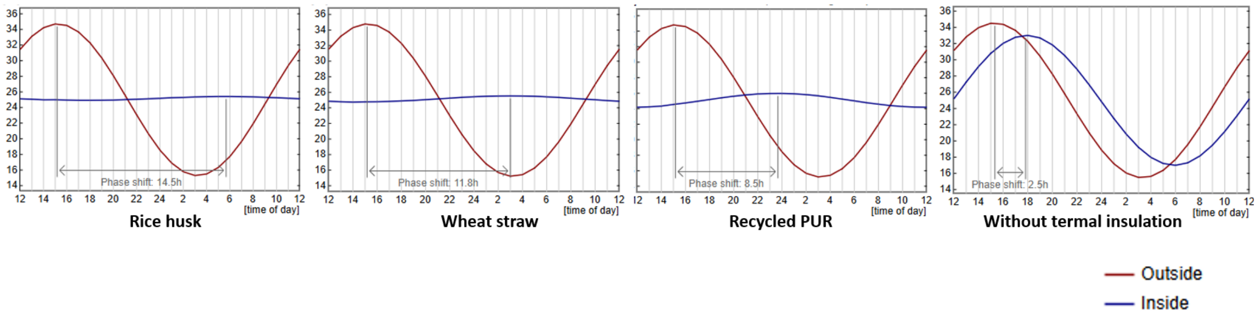
Table 3: Results of thermal performance

Property	Unit	Wall without thermal insulation	Wall M rice husk	Wall M Wheat straw	Wall M Recycled PUR
U Value	W/m^{2}K	1.613	0.168	0.148	0.201
Time Lag	h	2.50	14.50	11.8	8.50
Decrement factor	Dimensionless	1.2	40.50	24.1	11
Heat storage capacity (whole component)	Kj/m^{2}K	60	98	78	69
Thermal capacity of inner layers	Kj/m^{2}K	23	49	39	34

The U-values for the insulated walls were below 0.21 W/m^{2}K, with the lowest values recorded for wheat straw (0.148 W/m^{2}K) and rice husk (0.168 W/m^{2}K), both outperforming the recycled PUR panel (0.201 W/m^{2}K) and dramatically improving upon the uninsulated configuration (1.613 W/m^{2}K).

Regarding thermal inertia, the time lag was substantially extended with natural insulation: rice husk and wheat straw walls achieved time lags of 14.5 and 11.8 hours, respectively, compared to 8.5 hours for PUR and only 2.5 hours for the uninsulated wall. This indicates better delay in heat transfer and improved indoor thermal stability, as further illustrated in the surface temperature profiles (Figure 4), where both bio-based materials maintained a more consistent interior temperature throughout the day.

Figure 4: Monthly Indoor Air Temperature under Passive Conditions for Different Insulation Scenarios.



The decrement factor, representing the attenuation of temperature fluctuations, (Rojas-Herrera, Martínez-Soto, Avendaño-Vera, & Cárdenas-R., 2024) was significantly reduced for the straw (24.1) and rice husk (40.5) configurations, confirming their superior dampening performance over PUR (11) and the uninsulated wall (1.2).

In terms of heat storage capacity, rice husk again performed best with a value of 98 kJ/m^{2}K, followed by wheat straw (78 kJ/m^{2}K) and PUR (69 kJ/m^{2}K). These values suggest enhanced thermal buffering, especially beneficial in cold-climate conditions with high diurnal thermal amplitude.

Overall, the results validate the effectiveness of rice husk and wheat straw as natural insulating materials, offering not only competitive thermal resistance but also greater stability and resilience against temperature fluctuations in high-altitude Andean housing applications.

3.4 3.4. Dynamic simulation in DesignBuilder

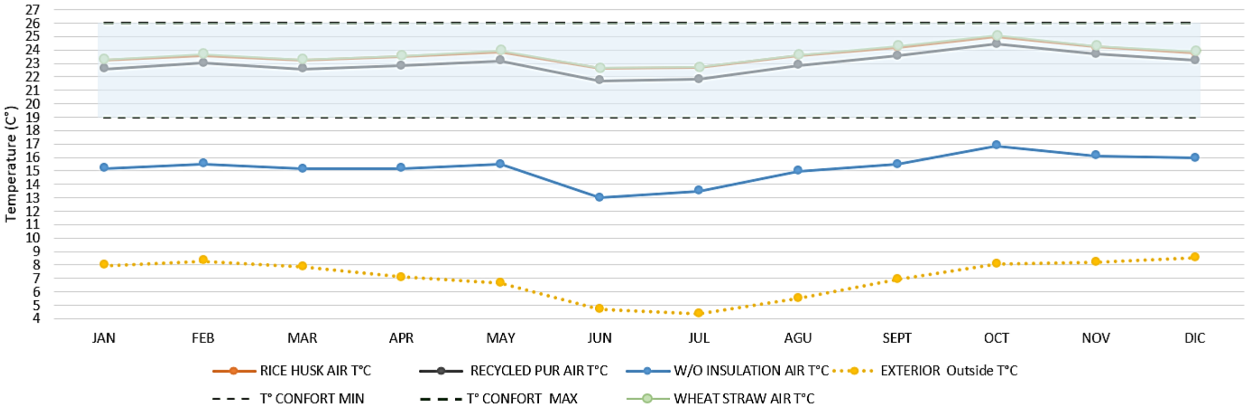
The dynamic thermal simulations, conducted without active HVAC systems, were used to assess the passive thermal performance of the modular prototype under four insulation scenarios. As shown in Figure 5, the bio-based insulation materials—wheat straw and rice husk fiber—significantly improved indoor thermal stability compared to the uninsulated configuration.

Both wheat straw and rice husk maintained indoor temperatures close to or within the comfort range (19–25 °C) for most of the year, with wheat straw exhibiting slightly better performance during the coldest months, and rice husk offering more uniform behavior across seasons. The recycled PUR scenario reduced thermal losses relative to the uninsulated wall, but still fell below comfort thresholds during winter.

In contrast, the uninsulated configuration closely tracked outdoor temperature fluctuations, highlighting the essential role of insulation in maintaining indoor comfort. Overall, the results confirm that combining bio-based insulation with passive design strategies and airtight modular construction can deliver thermally stable indoor environments in high-altitude Andean climates, supporting the development of low-energy housing solutions without dependence on mechanical heating.

Figure 5 illustrates the monthly average indoor air temperatures for each insulation scenario, compared against the outdoor temperatures and the defined thermal comfort range, under passive conditions without HVAC intervention.

Figure 5: Monthly Indoor Air Temperature under Passive Conditions for Different Insulation Scenarios.



4. Conclusions

This study evaluated the thermal performance of a modular wall system based on the Wikihouse Skylark 250 platform, incorporating bio-based insulation materials for high-altitude climates in the southern Peruvian Andes. Steady-state hygrothermal analysis and dynamic thermal simulation enabled a comparative assessment of rice husk fiber, wheat straw fiber, and recycled polyurethane (PUR) against an uninsulated reference.

The results show that natural fibers can stabilize indoor conditions and reduce the pronounced temperature swings typical of high-altitude climates without HVAC. The modular configuration proved effective as a flexible platform for low-energy housing solutions.

The system's cavity-based design enables the integration of locally available fibers via blowing, enhancing thermal performance with natural materials. Beyond the cavity, the construction logic allows adaptable finishes and detailing, facilitating the use of vernacular resources and improving both cultural relevance and sustainability in rural and peri-urban highland contexts.

In addition to technical performance, long-term adoption in the Andean highlands depends on cultural and social factors. Traditional methods—such as adobe, quincha, and sillar—remain central to local identity and community-based building. The Wikihouse approach can complement rather than replace these practices by providing a digital, prefabricated framework that adapts to vernacular finishes and local materials. Its success will rely on cultural acceptance and community involvement, ensuring it functions not only as a low-carbon technical solution but also as a socially grounded housing strategy.

The main limitations of this work are the reliance on simulations and the absence of field validation. While the results offer robust comparative insights, they do not capture long-term effects related to moisture dynamics, biodegradability, and life-cycle performance of the insulation materials. Future research will prioritize empirical testing under real conditions, long-term hygrothermal monitoring, and life-cycle assessment, alongside the integration of vernacular construction practices to strengthen both technical performance and social acceptance.

Finally, this paper represents the first stage of a broader research effort that seeks to bridge digital modular construction with vernacular traditions in the Andean context. By positioning agricultural residues within modular systems, it lays both a technical and cultural foundation for advancing sustainable, context-sensitive housing solutions.

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BUILDING INTERIORS WITH PRIVATE-CONSUMPTION COMPANIES: FROM PACKAGING TO HOUSING THROUGH CONCURRENT ENGINEERING

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ABSTRACT

The construction industry is one of the largest contributors to global environmental degradation, primarily due to emissions, energy consumption, and material use. This research proposes integrating recycled consumer packaging—such as plastics, tires, and Tetra Pak cartons—into the design of interior building elements as a strategy for sustainable construction. This research proposes the integration of recycled consumer packaging—such as plastics, tires, and Tetra Pak cartons—into the design of interior building elements as a strategy for sustainable construction. The study examines the environmental impact of conventional construction, highlights sustainable building practices, and discusses the roles of governments, private-consumption companies, and financial institutions in promoting a circular economy. Results indicate that packaging materials, when designed for secondary use, can provide cost-efficient interior solutions, foster long-term relationships between companies and consumers, and reduce construction-related emissions. The research introduces Concurrent Engineering as a design principle, ensuring that packaging is conceived from the outset for dual purposes: consumer product protection and later reuse in housing interiors.

Keywords: Sustainable construction; Consumer Packaging; Housing Interiors; Private-consumption companies; Concurrent Engineering.

1. Introduction

High interest rates and the rising cost of construction materials increasingly constrain the affordability of housing. This study explores an alternative pathway: **building interiors with private-consumption packaging.** The concept envisions packaging designed for reuse in interior finishes such as flooring, walls, and furniture. This approach requires coordinated action between governments, private-consumption companies, the construction industry, and financial institutions, while public acceptance depends on clear communication of economic and environmental benefits. The novelty of this study lies in applying Concurrent Engineering to consumer packaging, ensuring its dual role as both a marketing tool and a construction material for sustainable housing interiors, thereby integrating governments, private consumption companies, construction industries, and financial institutions. Sustainable buildings can minimize emissions, energy consumption, and material waste while enhancing occupant comfort and productivity.

1.1 Background - Environmental Impact of Construction

Buildings are a leading source of sulfur dioxide emissions, generated through the combustion of materials such as cement and steel, as well as from heating and cooling systems (Berry et al., 2019). These pollutants pose health risks and contribute significantly to climate change.

1.2 Potential of Recycled Consumer Materials

Recycled packaging offers significant opportunities to generate new raw materials for interior construction:

- **Plastic Solid Waste (PSW):** Repurposed into wood-like material for furniture, interior partitions, and external green walls (Herrera et al., 2018).
- **Tetra Pak and carton-based packaging:** Beverage cartons and bundled cases (e.g., toothpaste boxes, multipacks of milk containers) can be redesigned for modular secondary use. When collected and processed, these cartons can be transformed into thermo-acoustic panels, flooring, and furniture components (Ecuaplastic S.C., 2020). Smaller cartons can also be reused directly as household organizers, demonstrating relationship marketing opportunities.
- **Waste tires:** Used in insulation, acoustic panels, and as structural elements in mobile interior partitions and furniture bases (Mohajerani et al., 2020).

These cases illustrate how carton packaging, alongside plastics and tires, can play a crucial role in delivering affordable interior solutions.

1.3 Socioeconomic Implications

While prototypes and case studies exist, three barriers persist:

- The **lack of Concurrent Engineering design** in consumer packaging prevents integration of reuse pathways from the outset.
- The **absence of formal regulations** to guide the safe reuse of packaging in construction.
- Limited **industry-wide adoption**, as firms prioritize short-term sales over long-term reuse strategies.

Government policies and credit incentives are essential to encourage builders and consumers to adopt recycled materials. Without such frameworks, the potential of packaging-to-housing systems remains underutilized.

2. Methodology

This research is based on a qualitative and exploratory approach, structured around three complementary methods:

- **Literature Review** – Academic sources, government documents, and industry reports were reviewed to identify the environmental impact of construction and the state of recycling practices for plastics, tires, and carton packaging.
- **Case Study Analysis**– Existing prototypes and commercial products using recycled materials were examined, such as thermo-acoustic panels from Tetra Pak (Ecuaplastic S.C., 2020) and recycled plastic lumber walls (Herrera et al., 2018). These cases provide practical insights into how consumer waste can be revalorized.
- **Concurrent engineering framework** – The study applies the principles of concurrent engineering to analyze how packaging design can be integrated with construction needs from the earliest stages. This includes evaluating toothpaste and soap boxes, as well as multipack milk cartons, as potential secondary-use elements for interior finishing.
- **Regulatory and Financial Analysis:** Exploration of government and banking roles in incentivizing adoption.

The methodological contribution is the proposal to **shift packaging design from a marketing-centered approach to a concurrent engineering perspective**. This means that consumer goods packaging is not only optimized for sales but also pre-designed for reuse in housing interiors.

Finally, the analysis incorporates a **socioeconomic lens**, assessing the role of regulations and financial incentives (e.g., flexible mortgages for homes that are progressively completed through natural consumption) as enablers of this model.

Table 1 summarizes the reuse potential and associated CO_2 savings per unit for selected packaging materials adapted for interior housing applications. These estimations are based on comparative life-cycle assessment (LCA) data aligned with ZEMCH sustainable construction standards. The results emphasize the environmental benefits of extending packaging material lifecycles through creative reuse strategies in housing and interior design contexts.

Table 1: Summary of Material Reuse Potential and CO_2 Savings

Material	Reuse applications	Environmental impact	Co_2 Savings (kg/unit)	CO_2 Savings Calculation Methodology Avoided CO_2 = (virgin embodied CO_2 per kg) × (mass used per functional unit) × (reuse efficiency factor)
PLASTIC BOTTLES	Furniture, partitions, green walls	Diverts from landfills and reduces plastic production demand	1.7 – 3.4	3.0 kgCO_2/kg × 0.025 kg × 0.9 × (25–50) = 1.69–3.38 kg CO_2 saved / panel.
TETRA PAK	Flooring, panels, furniture	Reduces virgin aluminum and paper material use	2.0 – 5.4	5.0 kgCO_2/kg × 0.03 kg × 0.9 × (15–40) = 2.03–5.40 kg CO_2 saved / panel.
TIRES	Insulation, structural elements	Reduces rubber waste and extends tire life cycle	6.22 – 9.95	6.5 kgCO_2/kg × (9 kg × 0.125–0.20) × 0.85 = 6.22–9.95 kg CO_2 saved / insulation module.
KITCHEN APPLIANCE BOXES (e.g., refrigerator or kitchen box)	Storage for seasonal items such as Christmas decorations or clothing for upper-level closets	Promotes household material recirculation and waste minimization	0.8 – 1.2	1.2 kgCO_2/kg × 1.0 kg × 0.9 = 1.08 kg CO_2 saved / box (typ. 0.8–1.2).
DISH BOXES	Reused as organizers for notebooks or as kitchen trash bins	Encourages secondary functionality and reduces packaging waste	0.43 – 0.81	1.2 kgCO_2/kg × (0.4–0.75 kg) × 0.9 = 0.43–0.81 kg CO_2 saved / small box.
SMALL/MEDIUM BOXES	Repurposed as trash bins for bedrooms and bathrooms	Minimizes single-use packaging and landfill contribution	0.43 – 0.86	1.2 kgCO_2/kg × (0.4–0.8 kg) × 0.9 = 0.43–0.86 kg CO_2 saved / box.
FURNITURE BOXES	Converted into bookshelf panels or modular shelving components	Extends material lifecycle and promotes circular design	1.08– 2.16	1.2 kgCO_2/kg × (1.0–2.0 kg) × 0.9 = 1.08–2.16 kg CO_2 saved / converted furniture box.

3. Results and discussion

3.1 Environmental impact of construction

Buildings are a leading source of sulpur dioxide emissions, generated through the combustion of materials such as cement and steel, as well as from heating and cooling systems (Berry et al., 2019). These pollutants pose health risks and contribute significantly to climate change. Concurrent Engineering (CE) highlights that material and design choices should be considered not only for performance, but also for post-consumption reuse potential.

To operationalize this proposal, the adoption of **Concurrent Engineering (CE)** principles is essential. CE provides a framework where **cross-functional design teams**—comprising packaging engineers, architects, materials scientists, sustainability experts, construction professionals, and financial stakeholders—collaborate from the earliest design stages. This ensures that consumer packaging is conceived **not only for product protection on shelves** but also for its **secondary life as an interior construction component.**

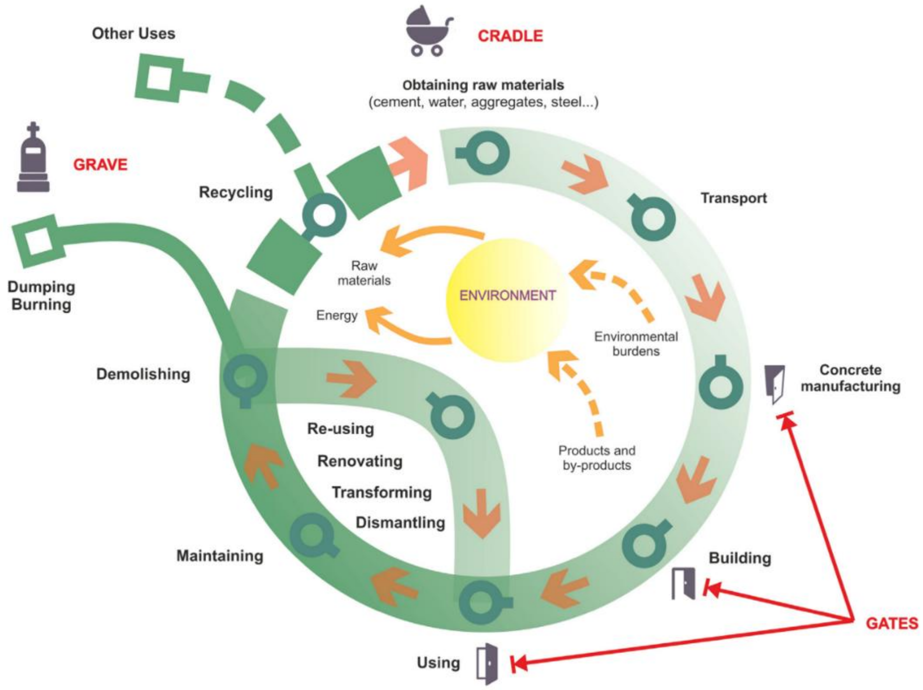
Key CE mechanisms include:

- **Parallel Task Execution:** Packaging design, material testing, and prototype development for building applications proceed simultaneously.
- **Early Supplier Involvement:** Packaging manufacturers and builders align specifications for dual purposes.
- **Modular Geometry Design:** Standardized dimensions (e.g., 150/300/600 mm) allow seamless integration into interiors.
- **Lifecycle Assessment Integration:** Environmental, structural, and thermal performance are assessed across both life stages.

- **End-User Feedback Loops:** Consumer validation ensures practicality, safety, and aesthetics of reused materials.

By embedding these mechanisms, packaging evolves into a **dual-purpose** resource that reduces construction costs, lowers emissions, and strengthens consumer-brand relationships.

Figure 1: "The life cycle of a building



Font: (authors' diagram based on Josa et al., 2007)" (Sánchez-Garrido, Antonio J., and Víctor Yepes 578)

3.2 Potential of recycled consumer materials

Recycled consumer packaging offers significant opportunities to generate new raw materials for interior construction. Examples include:

- **Plastic Solid Waste (PSW):** Repurposed into wood-like material for furniture, interior partitions, and external green walls (Herrera et al., 2018).
- **Tetra Pak and carton-based packaging:** Beverage cartons and bundled product cases (e.g., toothpaste boxes or multipacks of milk containers) can be redesigned for modular secondary use. When collected and processed, these cartons can be transformed into thermo-acoustic panels, flooring, and furniture components (Ecuaplastic S.C., 2020). Smaller cartons can also be reused directly as organizers for household items, providing both functional storage and an example of relationship marketing between companies and consumers.
- **Waste tires:** Used in insulation, acoustic panels, and as structural elements in mobile interior partitions and furniture bases (Mohajerani et al., 2020).

These applications demonstrate that carton packaging, in addition to plastics and tires, can play a crucial role in providing affordable interior solutions. Designing packaging for durability and reuse through **Concurrent Engineering** could strengthen consumer-brand relationships while promoting a circular economy in the construction sector.

Figure 2: Example of Tetra Pak Reuse in Flooring and Construction materials with fire-weather resistant and thermo-acoustic characteristics – Ecuaplastic - Ecostudio.

Figure 3: Toothpaste Boxes Reused as Organizers – Naty Gloss

3.3 Socioeconomic implications

While prototypes and case studies exist, three barriers remain:

1. Lack of Concurrent Engineering in consumer products – industries design packaging for marketing and sales, not for post-consumption reuse. Toothpaste and soap boxes, for example, could easily be redesigned as stackable modules for libraries, kitchens, or storage. Milk cartons and multipack cases could become panels for interior walls or organizers.
2. Absence of formal regulations – without standards that validate reused materials, builders and consumers face uncertainty.
3. Limited industry-wide adoption – current efforts remain marginal and not integrated into housing supply chains.

Proof of feasibility comes from the successful application of **Concurrent Engineering (CE)** in complex industries such as **automotive and aerospace,** where cross-functional teams design components for production efficiency, safety, and lifecycle reuse. Translating these practices into consumer packaging suggests that everyday items—such as toothpaste boxes, multipack cartons, or soap cases—could likewise be engineered as dual-purpose products, optimized both for product marketing and for post-consumer reuse in housing interiors.

1. Relationship marketing can be strengthened through consumer engagement in reuse, then Socioeconomic and Marketing Implications adoption requires:
2. CE integration in packaging design.
3. Regulations for safe material reuse.
4. Industry-wide adoption to maximize circular economy benefits.

The contribution of this study is to show that Concurrent Engineering in packaging design can become a cost-reduction mechanism in sustainable construction. If financial institutions allow mortgages for partially completed homes, interiors could be progressively finished through the natural consumption of goods. This model creates new bridges between industries, consumers, builders, and banks.

3.4 Policy and industry integration framework

Governments and financial institutions can incentivize the use of recycled packaging through:

1. Tax reductions for sustainable housing projects.
2. Flexible mortgage schemes for homes progressively completed with recycled materials.
3. Standards for minimum material quality, safety, and thermal performance.

4. Conclusions (and future work)

This research demonstrates the untapped potential of **Concurrent Engineering (CE)** to transform consumer packaging into a driver of sustainable construction. By designing packaging for dual functionality—from product protection to secondary use in housing interiors—industries can contribute to the circular economy, reduce construction costs, and engage consumers in the progressive completion of their homes.

The study identified three persistent barriers: the lack of CE in packaging design, the absence of formal regulations to validate reused materials, and limited industry-wide adoption. Overcoming these requires cross-sector collaboration among private-consumption companies, builders, governments, and financial institutions. If banks adopt flexible mortgage models that allow homes to be progressively completed through natural consumption, the economic and environmental benefits of this system could be fully realized.

CE can transform consumer packaging into sustainable construction resources, creating cost savings, environmental benefits, and strengthened consumer-brand relationships. Future work should focus on:

- **Pilot projects** with packaging and construction companies to validate structural, thermal, and safety performance at scale.
- **Consumer studies** to assess acceptance and behavioural impacts of progressive home completion.
- **Policy development** to establish standards for packaging-based materials and to incentivize adoption through sustainable mortgages and tax reductions.
- **Cross-industry agreements** to align packaging design, supply chains, and housing needs under CE frameworks.

The ***"boom" of cost reduction in sustainable construction*** will only occur when packaging is conceived as a material resource from its design stage and when financial institutions recognize progressive completion models tied to consumer behaviour. This study contributes a practical framework for linking daily consumption with housing construction, offering pathways to reduce environmental impact while fostering long-term value creation for companies, consumers, and society.

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ENVIRONMENTAL AND PRODUCTIVE INSIGHTS FROM CHILE'S FIRST 3D-PRINTED HOME PROTOTYPE

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ABSTRACT

This article presents the development and projected implications of the first 3D-printed housing prototype built in Chile, with a focus on its environmental and productive dimensions. The initiative aimed to test the feasibility of 3D-printed construction within the country and explore its potential for addressing housing needs. The project was carried out in collaboration with national companies: wall components were printed in a university laboratory and assembled on-site, complemented by additional tasks to complete the construction process. The design incorporated bioclimatic strategies and complied with local standards for thermal efficiency and seismic resistance, employing an insulated envelope reinforced with structural elements and connectors. Parametric programming was used to generate adaptable housing models suitable for various climates and uses. The prototype was completed and it has undergone simulation, real-time monitoring, and public exhibition. To date, it has shown promising thermal performance, though issues such as air leakage and comfort levels have been identified. The use of parametric tools enables the design of housing units in varying sizes, with components that can be automated and fabricated either on- or off-site. This experience highlights the local viability of 3D-printed housing as a sustainable and scalable construction method with mass-market potential.

Keywords: Housing, 3d-printed Construction, Environmental Performance, Mass-customization

1. Introduction

The new 3D printing technologies in construction has allowed for the execution of several housing examples (Placzek and Schwerdtner, 2024). However, most have been built in warm climates, and without examining their local adaptation and potential for mass production. The objective of this article is to present the development and implications of an innovative 3D-printed housing prototype, specifically analyzing its environmental and mass-production conditions.

Large 3d-printers or manipulating robots allows for additive manufacturing of building elements using on rapidly hardening fluid mixtures controlled by digital designs (Arrêteau et al, 2023). This capability allows for the production of entire buildings or parts, in shorter times and with fewer resources than conventional methods (Bello and Memari, 2023). This results in fewer accessories, waste, and manual labor, contributing to the sustainability and safety of construction projects, as well as production efficiency. Its application is usually focus on large elements subjected to simple stresses, such as walls or main covers, which must be complemented with insulation, structural reinforcements, as well as foundations, services and roofs to get a comprehensive building. Several housing examples built around the world demonstrate the potential of this technology and its operational adaptation but without establishing standards or offering mass-produced solutions to date (Youssef and Abbas, 2023; Gardan et al, 2025). But, the production for large-scale projects requires local adaptations and integration for houses of different sizes or geographic areas. Also, it must ensure habitability and compliance with regulations in order to be adopted in mass programs.

In Chile, mass production of housing is required for a wide variety of climates, all of them in seismic zones. State programs and private initiatives promote the industrialization and sustainability of construction with regulations for thermal insulation and resistance performance (MINVU, 1992 and MMA, 2019). Furthermore, experimentation with new technologies and construction solutions has been encouraged. The University of Bío-Bío in southern Chile, which has a track record in sustainable building and multiple laboratories, has implemented a full-scale prototyping laboratory (PEP-Lab), installing an industrial robot and a large printer to test 3D printing in construction. It also signed agreements with national companies to develop a 3D-printed housing prototype, called "Casa-Semilla" (seed-house). In line to affordable housing policies of the country (Minvu, 2023) and global sustainable development goals, like 9, 11 and 13 (UN, 2015), offering a model that can be replicated in seismic and diverse climatic contexts.

2. Methodology

2.1 Design

The prototype was agreed to install in a demonstration site of the collaborating real estate company, in the city of Concepción, at latitude 36°46´22", which has a temperate-seasonal climate. Construction was planned with the contribution of private companies in products and on-site work, with design, supervision and the printing of walls in the university laboratory. The design of prototype was intended like an initial example of diverse housing solutions, as well as its environmental suitability and seismic resistance, with accomplish of local regulations and execution capacity.

The design contemplated a minimal floor plan that must suggest domestic possibilities and feasibility of execution, with three interior spaces: living-dining room, bathroom, and bedroom. In one-story volume longitudinal on the east-west axis, in order to have a sunny side with openings of the three rooms to get direct solar radiation and natural lightning, and the opposite shaded side with the circulation and entrance on to the street, for public accessibility and lightning contrast to the interior, as well small windows to get natural crossed ventilation. The shape sought to combine straight parts, to accommodate conventional furnishings and regular spaces separations; with arched parts, showcasing the printing´s ability to create curved profiles with greater stability and appearance uniqueness. Thus, the design defined continuous walls for the perimeter and internal divisions, with a straight roof, slightly inclined in the center to collect rainwater and reduce their external presence to promote printed walls. But with extended eaves to protect from frequent rains and excessive solar radiation in summer. The bathroom adopts a central position to concentrate the sanitary services and support a kitchen counter on the side, with a possibility to extend transversely to the volume, to facilitate the expansion of the ends with diverse enclosures. Four main wall sections were defined, separated by larger openings, to accommodate the enclosures and the living perimeter with exterior continuity and interior integration, reinforced by rounded corners and arched sides. In order to contribute to the building's resistance to overturning due to lateral seismic thrusts and a novel and attractive appearance.

Based on these definitions, a parametric program was developed about the prototype form, with geometric controls in center distances, centerlines, and radius lengths to establish different layout magnitudes and enclosure configurations. The layout, corresponding to a minimum plan with three enclosures, was developed in its architectural and structural designs, in addition to the construction planning. The walls were designed with double vertical planes printed with cementitious mixture to allow for interior voids for additional thermal insulation, services, and structural reinforcements of pillars and chains (according to Delavar et al, 2023 and MINVU, 2011). Continuous underground concrete foundations were planned, with a reinforced chain with rebar along the wall axes, secured to interior columns with a central tensioner each, tied at the top edge. A metal connecting beam was also included between the walls, and the roof was constructed of a lattice structure of metal profiles. The installation of a metal roof with thermal insulation and a ceiling was considered, as well as doors, windows, sanitary fixtures, kitchen cabinets, floors, and a spray-on epoxy coating to expose the roughness of the print.

2.2 Construction

The construction was built on-site while the walls were being printed in the university laboratory, with a professional coordination team, more operators at both locations. The walls were divided into seven sections weighing an estimated maximum of 1.5 tons each to facilitate transport and assembly. Specific programming was carried out for each section and set of prints, in addition to mixing and printer control tests, defining a layout to contain the columns. Five separate printer work sessions were then conducted, depending on the availability of personnel and materials in the laboratory. The machine was operated in different sessions for a total of 55 hours, with continuous laydown for 21.5 hours to execute 48 m2 of walls. An additional session was also performed for nine smaller pieces of low wall in the bathroom and outdoor planters. The elements were protected from moisture and moved to the site a week after each session to ensure hardening. Some segments were replaced, and the amount of water added to the mix, along with the delivery time and placement speed, had to be adjusted according to the environmental humidity and printing layouts.

On-site, the wall axes were laid out on the ground, and foundations were excavated and filled with continuous concrete. A foundation chain with rebar was constructed, connected to vertical tension rods to form the columns, and a concrete floor was filled. The walls were then assembled, fitting the column spaces into the tension rods and applying a bond seal at the bases and junctions between walls. The columns were then filled with concrete, and a wooden top profile was installed to accommodate the upper chain iron, which was also filled. The wall spaces were filled with thermal insulation and service cuts were made. A roofing structure was then built using lightweight metal bars, forming an oval perimeter with a double inward slope. It was covered with metal roofing over wooden planks, along with a plaster ceiling and insulation. Wooden doors and vinyl windows with sealed double-panes were installed, kitchen cabinets, sanitary fixtures and electrical wiring were installed. The walls were coated with an elastomeric liquid with sprayed cork to maintain the roughness of the construction. Finally, indoor and outdoor floors were laid, planters and the outdoor green area was completed, as well as signs displaying photos of the process and participating companies. Construction took place over six months, involving 40 work days with two to six workers, plus professional supervision.

Figure 1: Prototype Construction; Left: Printing of walls in university lab; Center: Assembly of walls on-site; Right: Prototype executed

The prototype is currently maintained with a schedule of visits for professionals, students or the public. Visits are attended by a research member with an average of 100 people per month. An opening ceremony was also held, with nearly 200 attendees and widespread social media coverage. The feedback received was mostly positive regarding the technological innovation, spatial quality, and lighting, with varying opinions regarding the roughness of the walls and expected costs, as well as seismic stability and climate protection.

3. Results

3.1 Environmental analysis

The prototype was designed to comply with local regulations for housing, in particular thermal properties, and also environmental performance was reviewed by simulation and physical monitoring. Chilean construction law requires housing envelopes to meet thermal transmittance values to promote energy efficiency according to the climate zone (MINVU, 1992). Stricter special plans are also required in large cities with urban pollution (MMA, 2019). Furthermore, starting in November 2025, the law will increase transmittance requirements and add conditions for condensation infiltration, ventilation, and windows to improve habitability. Also, certification of expected energy consumption levels will be mandatory for new housing.

The prototype obtained legal approval of construction like exhibit building, which required to approve urban distances and built surface, accessibility conditions, natural lighting, fire and acoustical insulation, and seismic resistance defined with analytical verifications, which are currently being verified through displacement sensors. Regarding the thermal conditions for housing, the building envelope of prototype regards the addition of mineral wool to the ceiling, polystyrene spheres in wall cavities, and double-glazed windows, in addition to an appropriate distribution. The composition of the envelope has an estimated transmittance of 0.38 W/m2K for the roof, 0.645 W/m2K for the walls, and 2.9 W/m2K for the windows, with glazing percentages of 29.4%, 0%, 37%, and 6% per façade. This meets the current legislation for the zone and is close to the new regulations (which require 0.33 W/m2K, 0.6 W/m2K and 2.4 W/m2K, and maximus of 60% respectively).

Compared to the country's other climate zones, the prototype is located in one of coldest weather. Therefore, most zones require higher transmittance, and a few are stricter, up to approximately 20%. Such can be increased, with higher insulation products in wall cavities or by increasing their thickness. In roofs or ventilated floors, if applied, it is easy to add more insulation or change products, as well as adding to the perimeters of foundations. Conversely, it can be reduced in warmer climates, allowing more space for installations. Door and window conditions also vary, but are adequately met with integrated products and maximum glazing with a corresponding arrangement of resistive walls. Ventilation and condensation requirements are similar. Regarding the required airtightness, which is established in three geographic area categories according to prevailing wind magnitudes, Concepción falls into the strictest (8.0 at 50 Pa ach), which can be met with meticulous sealing work. The 3D-printed construction provides horizontal continuity of the walls, which is beneficial for reducing infiltration, but the rough edges also increase junctions between windows and ceilings, such as service entrances, which must be treated in two sealing phases.

The energy simulation of prototype was done through Design Builder software and Energy Plus engine, with assumption of regular housing occupation and thermal transmittance of materials according building design. The results revealed a total annual demand of 2,228.8 kWh/year, equivalent to 79.6 kWh/m^2/year, and based on the national electricity cost, translates to approximately 448 USD per year. This corresponds to less than third of the national average per household and is about 20% lower when adjusted for equivalent surface area (CDT, 2018). Environmental monitoring for validation is being conducted using four indoor sensors measuring temperature, humidity, and CO_2, along with an outdoor weather station. A controlled thermal regime monitoring phase will be carried out later using a 12,000 BTU/H HVAC system, registering sensor data and conducting air infiltration measurements (blower door test), surface transmittance analysis, and thermographic imaging. Initial results from the sensors over a two-week period in summer, under free oscillation conditions (without climate control), recorded an average indoor temperature of 23°C, with daily highs of 27–29°C in the afternoons and lows of 17–18°C at dawn. Relative humidity, which varies inversely with temperature, averaged between 51% and 53%, with maximum values between 61% and 63% and minimum values between 34% and 39%. CO_2 levels averaged between 415 ppm and 432 ppm, with maximum readings of 493–597 ppm and minimum values of 361–376 ppm. According to the ASHRAE 55 comfort temperature ranges, the prototype maintained comfort conditions 48.21% of the time, which is higher than national records for similar homes, and also CO_2 levels are proper according ASHRAE 62.1 These findings suggest that the house can provide thermal and indoor air comfort without additional climate control.

Thermal transmittance monitoring of the envelope has revealed values consistent with those considered in the analysis, based on material data. The infiltration rate was substantially lower than required, so a new sealing process is being carried out to restore it. The environmental review of the prototype indicates adequate thermal and energy performance, with areas for improvement. It also demonstrates adequate adaptability to the country's different climatic zones, ensuring specific conditions, especially for colder areas. These results confirm compliance with current regulations and show how 3D-printed housing can support national energy and housing programs, adapting insulation and material strategies across different climate zones.

3.2 Mass-customization potential

The potential for mass production of 3D-printed homes, based on the "Casa-Semilla" experience, has been developed through an execution strategy, parametric programming of design variations and integration with BIM modeling, in order its adaptability to other regions with similar climatic or seismic challenges.

The machinery used to print the prototype walls demonstrated adequate capacity and versatility, with proper personnel training, procedures, and technical assistance. In particular, the Bemore-Pro printer and the Kuka R250 robot enabled the pieces to be printed, supported by various mixing pumps and control programs. Both systems (gantry and robotic arm) feature various international suppliers, with equipment that varies fundamentally in reach dimensions. It is important to consider that printers can be moved directly to the on-site work site, as verified by the university team. Robots require additional mobile support and more delicate calibration, but are more versatile movements and tools. In both cases, logistical management is more efficient for larger print volumes. The pumps were tested with a medium capacity (120 liters), but for larger volumes, it is recommended to install silos and larger pumps with more detailed controls. Weather protection with tents or work sheds, as well as protectors for the finished parts, ensure they maintain moisture and harden properly.

For the printing of prototype walls and preliminary elements, an architect-programmer, a printer or robot operator, and another pump operator were involved, along with occasional assistants and temporary, but more intensive, responsibilities for initial preparation and subsequent cleanup. This staff requires technical or professional training and brief specific training, in addition to occasional technical assistance from suppliers or other specialists for equipment and process adjustments. Furthermore, various mixtures have been tested, both prepared by suppliers (Lafarge and Sika) and in-house developments, applying standardized tests and preparation protocols. The work yields were achieved largely in relation to conventional construction tasks for the construction of thick walls and elements, with low accident rates and low resource use. Although the initial capital investment in equipment is high. Besides, special attention must be paid to the waste generated, as collapsed prints where the material can be reused, but also pieces discarded due to testing or lack of coordination that must be removed.

Parametric design programming allowed for the definition of the prototype layout and the development of different architectural variations of homes, with larger rooms and built surfaces, based on similar construction conditions. Nearly 100 layouts and five models were detailed, and a work interface was implemented to control variations, offering instructions for adapting the designs to different climates and sizes. This was tested with a group of architects, demonstrating adequate usability and design potential.

The generated geometric data can be integrated into construction information models (CIFs) through export in IFC format for detailing, incorporating conventional elements, and for project planning and management. This model also allows for environmental and structural analysis. Programming also allows for wall segmentation based on the machine's reach and material preparation, according to the planned layer width and performance, and in accordance with the considered structural strategy. Furthermore, this data can be processed for the printing path based on the perimeters, width, and height of the bead, with spiral or chained paths between sections. This model also includes process simulation and export of the control code. This allows for generating a continuous flow of information between variable designs and customized execution, linking construction management and visualization with users in interactive processes for adjustments during development (Albalkhy et al, 2024). This capability is unprecedented in industrialized construction systems and can support large, massive operations with detailed management and customized solutions.

4. Conclusions

The experience of the first 3D-printed home prototype in Chile has enabled a unique application of new parametric design and additive manufacturing technologies for housing, proving its local feasibility through a fruitful collaboration between private companies and a university laboratory. It has successfully complied with regulations, used local personnel and products, and has received positive public awareness, boosting its potential for residential development. However, it must be implemented to verify its productive capacity, housing performance, and social acceptance through collaborative efforts with local businesses and occupants. The prototype has also demonstrated adequate thermal performance for a seasonally temperate climate, with an insulating construction strategy, natural harvesting and ventilation that minimizes energy demand. It also boasts low resource use and rapid execution, contributing to the sustainability of the homes. It can incorporate energy from solar systems and materials with low carbon capture to achieve zero-carbon energy goals, further reducing its environmental impact. The construction process and design programming demonstrate the potential for execution of large complexes with multiple alternatives or diverse locations, applying advanced production technologies. The verification of local capabilities and the definition of environmental and productive possibilities are a specific contribution of this experience. The global efforts in 3D-printed housing are concentrated in developing procedures, but it must advance toward sustainability and mass adoption. Then, Casa-Semilla is a unique kick-off of collaborative development and local spread, which must be adjusted to the current requirements and processes of the residential industry. The strategies tested on thermal performance, parametric adaptability, and structural reinforcement are scalable to other Chilean and Latin American regions, extending their applicability. Unlike most international experiences, Casa-Semilla demonstrates regulatory compliance for seismic regions and cold weathers, as well as potential for mass-customization, advancing 3D-printed housing toward sustainable and large-scale adoption.

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WIND TURBINE BLADES: FROM ENERGY SOURCE TO TINY HOUSE PROTOTYPES

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ABSTRACT

The rapid growth of global wind energy has exposed a pressing gap in end-of-life strategies for glass fibre–reinforced polymer (GFRP) blades, whose complex composition limits conventional recycling and disposal. Closing this gap demands more than technical fixes; it requires architectural approaches that reimagine waste as both material and spatial opportunity. This paper investigates the adaptive reuse of blade cross-sections to generate tiny house prototypes, demonstrating how industrial geometries can inform compact, habitable forms. Three prototypes, ranging from 10.1 m^2 to 21.2 m^2, were digitally modelled, and their architectural plans extracted to test design feasibility. Energy performance was assessed using PVWatts for Glasgow, comparing roof- and façade-based Building-Integrated Photovoltaic (BIPV) systems. Results showed roof systems providing the strongest outputs, with façades adding complementary capacity where surface area allowed. Beyond energy metrics, the study highlights the contribution of design in advancing circular economy practice—transforming decommissioned infrastructure into affordable, renewable-ready housing typologies. By positioning architecture as both a technical and cultural agent of reuse, the research addresses urgent environmental challenges while reinforcing global ambitions for resource responsibility, clean energy adoption, and resilient communities. Future work will extend into prototyping and socio-economic evaluation to move toward scalable application.

Keywords: Wind Turbine Blades, Tiny House, Prototype Design, NetZero Energy. Customisation

1. Introduction

At the end-of-life, first-generation wind turbines will leave behind a striking legacy: thousands of non-biodegradable, hard-to-reuse monumental blades, which are hard to dispose. Traditionally destined for landfills or incinerators, these fiber-reinforced polymer components resist easy recycling and confront the discipline of architecture with both an ecological challenge and a design opportunity. For architects committed to circular design, these aerodynamic artifacts are not waste—they are latent structures awaiting reinvention using adaptive use strategies. Recent reviews stress the urgency of reimagining end-of-life strategies for blades, situating architectural practice at the frontier of material stewardship and spatial innovation (Deeney et al., 2025; U.S. Department of Energy, 2025).

Advances in chemical recycling of epoxy-based composites are widening possibilities for architects and builders to engage with high-performance reclaimed materials. By leveraging solvent-assisted recovery and selective bond-cleavage techniques, researchers are unlocking routes that preserve fiber integrity for reuse in construction—transforming an intractable waste stream into architectural resource (De Fabritiis et al., 2025; Min et al., 2025). Simultaneously, life-cycle assessments show that integrating blade waste into building products such as concrete significantly lowers embodied carbon when compared to conventional disposal pathways (Manso-Morato et al., 2025). Another alternative is remanufacturing, which stands as a practical route for prolonging material service life at the end of use. Embedding design-for-remanufacture concepts and with closed-loop supply chain systems, supported by government policy could further help to redirect the potential negative drawbacks to this approach (Bag et al., 2019; Li, G., et al., 2018; Singhal et al., 2019).

From an innovative architectural perspective and for the built environment, these developments translate into two design trajectories. First, as form-as-found, where intact blade geometries become compact shelters, modular pavilions, or resilient tiny houses. Their aerodynamic curves offer not only structural capacity but also spatial drama—introducing a distinctive architectural language born from energy infrastructure. This paper situates the reuse of wind turbine blades within architectural scholarship, proposing a design-driven framework that merges adaptive reuse, modular housing strategies, and circular resource management. By doing so, it positions architecture as both mediator and innovator: transforming decommissioned infrastructure into spaces of habitation, resilience, and environmental repair.

2. Background

By 2030, 6.8 million tonnes of fibre-reinforced polymer (FRP) materials from decommissioned wind turbine blades will require end-of-life management — a figure quoted in the literature and from industry projections (Nelson et al., 2016). These composite materials are predominantly thermoset glass- or carbon-fibre-reinforced polymers, which are not biodegradable and difficult to process using conventional recycling methods (Santos et al., 2022; Zhang et al., 2023). Historically, decommissioned blades are taken to landfills or shredded for low-value applications, but this does not eliminate its end-of-life burden. A growing body of life-cycle studies shows that such landfill disposal and incineration generate greenhouse gas emissions and also lock in the embodied carbon of the original materials (Meijer et al., 2023; Andersen et al., 2023). Material down-cycling, such as using shredded blade material into concrete or cementitious products, may provide a reduced-emissions pathway; however, this may result in permanent loss of fibre functionality, leading to future disposal while also undermining long-term carbon and resource circularity (Santos et al., 2025).

By 2030, the global inventory of decommissioned wind turbine blades is projected to generate on the order of 400,000 tonnes annually of fibre-reinforced polymer (FRP) waste—a scale that demands robust end-of-life solutions (Jasińska et al., 2025). These blades are chiefly fabricated from thermoset polymers reinforced with glass or carbon fibres, materials that resist biodegradation and challenge conventional recycling pathways (Spini et al., 2024). In practice, most retired blades are landfilled or mechanically shredded into low-grade filler products—measures that simply shift the burden rather than resolve it. A growing suite of life-cycle assessments reveals that both landfill disposal and incineration lead to greenhouse gas emissions while failing to reclaim the embodied carbon embedded in the original composites (Sproul et al., 2024; Deeney et al., 2025). Recent scholarship urges integrated circular-economy action—recyclable blade design, standardized decommissioning, proven recycling routes, and enabling policy—so wind growth doesn't translate into tomorrow's waste burden (Deeney et al., 2025). In parallel, architectural upcycling is advancing, including prototypes that convert decommissioned blade sections into compact, modular tiny houses (Johst et al., 2024).

Tiny houses first gained momentum as a minimalist housing response, offering reduced footprints in both land use and resource demand. By deliberately constraining scale, they challenge conventional housing models and invite more efficient use of energy, space, and materials. Beyond lifestyle choice, they have become testbeds for sustainable architecture, where design integration and material innovation can push operational performance toward net-zero standards. Recent research demonstrates that when carefully designed, tiny houses can achieve substantial reductions in life-cycle emissions. A 2025 Danish assessment found that, compared with conventional housing typologies, tiny houses consistently lower embodied and operational carbon, particularly when coupled with renewable energy systems such as photovoltaics and energy storage (Vidal-Osses et al., 2025). At the same time, architects are experimenting with unconventional construction pathways. Repurposing decommissioned wind-turbine blades, for instance, illustrates how architectural upcycling not only diverts complex composite waste from landfills but also transforms industrial infrastructure into resilient living units (Johst & Chatzipanagiotou, 2024).

Together, these studies highlight that tiny houses are not inherently sustainable but gain real ecological significance when innovation is directed toward energy efficiency, renewable integration, and circular material strategies. In this sense, they act as architectural prototypes for future low-carbon living.

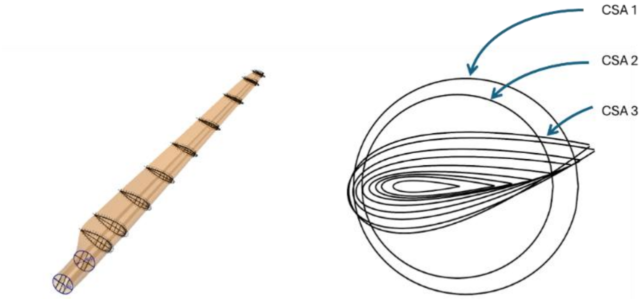
3. Method

The study was structured in two sequential phases to explore the circular economy potential of decommissioned GFRP wind turbine blades through architectural adaptation and renewable integration.

- Phase 1 focused on design exploration. Cross-sectional geometries of selected blades were analysed and translated into architectural floor plate concepts, which then informed the creation of tiny house prototypes in a digital modelling environment. This process not only examined dimensional feasibility but also tested how the inherent aerodynamic forms of blades serve as spatial modules. From these models, architectural drawings—including floor plans and elevations—were extracted to provide a technical and visual basis for further assessment.
- Phase 2 evaluated energy generation. Each prototype was integrated with Building-Integrated Photovoltaic (BIPV) systems across roof and façade surfaces. Energy output simulations were recorded and compared. This allowed for an appraisal of the energy potential of each design, identifying conditions under which a tiny house constructed from blade sections could be feasible

By combining geometric adaptation with renewable energy modelling, the methodology established a coherent design-to-performance framework, demonstrating how architectural practice can reposition end-of-life blades as both material and energy assets within circular housing strategies. Figure 1 shows the 3D model of a GFRP wind turbine blade and its cross-section areas (CSA) from secondary data (Steele et al., 2013).

Figure 1: Airfoil distribution along the blade length showing 11 discrete radial stations, and b) airfoil geometry and blade twist at these same stations

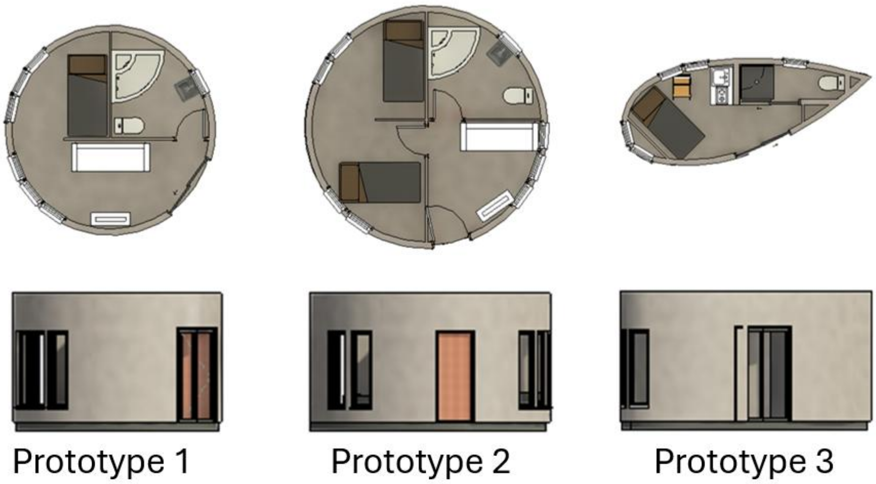


Font:. Steele et al.(2013)

4. Results/Impact

The design process produced three distinct prototype floor plans derived from blade cross-sectional areas of 16.6 m^2 (Prototype 1), 21.2 m^2 (Prototype 2), and 10.1 m^2 (Prototype 3). Prototype 1 adopts a circular layout featuring a combined living and single-bed sleeping area with a separate bathroom. Prototype 2 also follows a circular plan but expands to include an enclosed living space, a double-bed sleeping area, and a dedicated bathroom. Prototype 3 employs a distinctive airfoil form, integrating a compact living and single-bed sleeping area with an enclosed bathroom. As the spatial capacity of each prototype varies, comparative analysis is based primarily on floor area rather than occupancy levels. Figure 2 shows the architectural floor plans and elevations developed from the selected CSAs.

Figure 2: CSAs converted to floor plan. A. Prototype 1, Prototype 2 and Prototype 3



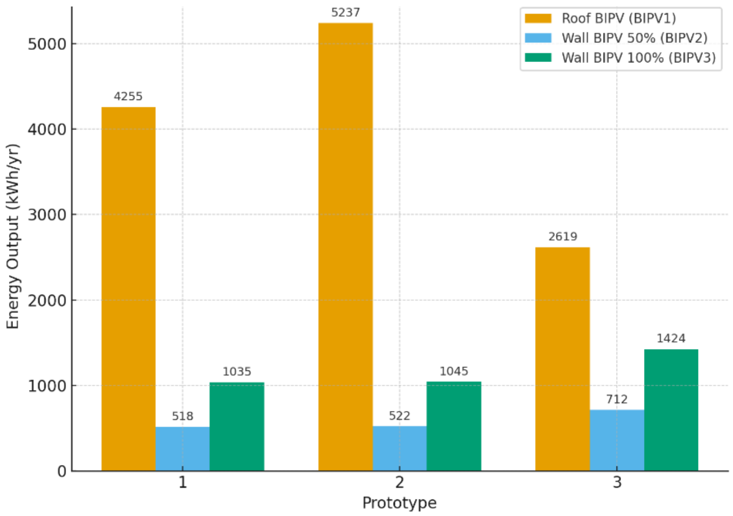
To assess renewable performance, Building-Integrated Photovoltaic (BIPV) systems were configured for each prototype, with outputs modelled using PVWatts for Glasgow conditions. The assessment considered three scenarios: roof-integrated BIPV (BIPV1), south façade integration at 50% coverage (BIPV2), and full south façade coverage at 100% (BIPV3). Table 1 presents the calculated energy outputs for each configuration, enabling a comparison of architectural form, floor area, and photovoltaic potential across the three design options.

Table 1: Prototypes and BIPV Output

Prototype	**Tiny House Dimensions**		**BIPV System Size**		**BIPV System Output (kWh/yr)**		
	CSA (Floor Area in m2)	South Wall Area	Roof System Size (kW)	Wall PV System Size (kW)	BIPV Roof (BIPV1)	BIPV South Wall (50%) (BIPV2)	BIPV South Wall (100%) (BIPV3)
1	16.6	9.6	2.6	1.6	4,255	517.5	1,035
2	21.2	11.3	3.2	1.6	5,237	522.5	1,045
3	10.1	15.4	1.6	2.2	2,619	712	1,424

Based on the roof or wall area of each Prototype, the BIPV systems were sized as follows. Prototype 1 – Rooftop BIPV was 2.5kW and the BIPV wall was 1.6kW. For Prototype 2 – Rooftop BIPV was 3.2 kW and the BIPV wall was 1.6kW. For Prototype 3 – Rooftop BIPV was 1.6 kW and the BIPV wall was 2.2kW. The total energy output for each BIPV system for each of the three prototypes was presented in the table, with the highest output being 5,237 kWh/yr/m2. This was the BIPV roof on Prototype 2 and the results is perhaps due its larger size. The lowest energy output was 517.5 kWh/yr/m2. This was the BIPV wall on Prototype 1 (See Figure 3).

Figure 3: Energy Output for each Prototype based on BIPV type



5. Discussion

This research demonstrates how architectural innovation can transform decommissioned wind turbine blades at end-of-life, into viable housing prototypes, underscoring the dual potential of addressing material waste and expanding sustainable dwelling options. By bridging circular economy strategies with design experimentation and energy modelling, the work directly contributes towards increasing adaptive reuse strategies, recycling/upcycling and circularity in the built environment.

Another critical consideration is that the research has potential towards advancing the United Nations Sustainable Development Goals (SDGs). There are three possible research pathways along this line of thinking. First, aligning with SDG 11: Sustainable Cities and Communities, the adaptive reuse of composite blades as structural modules highlights a path toward resilient, low-carbon housing in urban and peri-urban contexts (Johst & Chatzipanagiotou, 2024). Second, in line with SDG 7: Affordable and Clean Energy, the integration of Building-Integrated Photovoltaics (BIPV) within the prototypes illustrates how renewable energy technologies can be embedded into alternative housing typologies, strengthening the vision of net-zero living (Vidal-Osses et al., 2025). Third, supporting SDG 12: Responsible Consumption and Production, the methodology positions industrial waste as a design resource, advancing material circularity and reducing dependency on virgin construction inputs (Deeney et al., 2025). Collectively, these pathways establish a framework where architectural design not only responds to housing demand but also contributes to global sustainability targets.

This research opens pathways for several valuable extensions. One promising direction is the development of full-scale prototypes that can translate digital models into lived spaces, enabling deeper insights into architectural performance, energy behaviour, and user experience. Another extension lies in broadening the analysis to encompass socio-economic and policy dimensions, where cost modelling, regulatory alignment, and community engagement can enrich the architectural narrative. Together, these extensions advance the potential of blade-based housing from conceptual exploration to practical application, reinforcing its role within circular economy strategies and strengthening its contribution to sustainable design innovation.

6. Closing

This study demonstrates how decommissioned GFRP wind turbine blades can be repositioned as architectural resources, transforming an environmental challenge into an opportunity for sustainable housing. By translating blade cross-sections into digital prototypes and integrating Building-Integrated Photovoltaic (BIPV) systems, the research established a design-to-performance framework that connects form, geometry, and renewable energy potential. Roof-based BIPV consistently delivered the highest outputs, while façade integration offered complementary gains, confirming the viability of NetZero-oriented micro-dwellings.

The contribution of this work lies in advancing architecture's role within the circular economy: developing adaptive reuse strategies that divert composite waste, producing renewable-ready prototypes that reinforce energy resilience, and framing design as a tool for ecological innovation. In doing so, the study aligns directly with SDG 11 (Sustainable Cities and Communities), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production), positioning architecture as an active agent in achieving global sustainability targets.

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CHAPTER 6

MODULAR CONSTRUCTION AND SUPPLY-CHAIN MANAGEMENT

USING PLATFORMS TO ENABLE MASS CUSTOMIZATION IN CONSTRUCTION

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ABSTRACT

Low productivity and high costs in the Brazilian construction industry highlight the need for innovations that enhance efficiency and predictability. In this context, industrialization and the adoption of product platforms emerge as promising strategies. This paper presents a model for implementing product platforms developed as part of the Construa Brasil Project to support companies in structuring industrialized and modularly coordinated building systems. The model is composed of decision categories related to strategic decisions, such as market positioning, and the configuration of components and modules, enabling a balance between standardization and customization. The research follows a Design Science Research (DSR) approach for building and testing the model on its application in a national company experienced in modular industrialized construction. The case study demonstrates how platform adoption enables scale gains, variability reduction, and greater predictability in the production process, while maintaining flexibility to serve different market segments. The findings reinforce the role of product platforms as a driver for construction industrialization, offering practical guidelines for implementation. This study contribution proposes a model tailored to the Brazilian construction context and aligned with the sector's innovation and productivity goals.

Keywords: Open industrialization; Product platform; Modular construction; Mass customization.

1. Introduction

For a long time, the construction industry has been related to production inefficiencies associated with the traditional methods of construction and construction site production (Barbosa et al., 2017), such as long lead times (Hussin; Rahman; Memon, 2013), high costs (Nicholas; Steyn, 2017), and low productivity (Vrijhoef; Koskela, 2000). Industrialized building systems can be seen as an alternative to reduce waste and its effects on construction.

According to Bonev, Wörösch, and Hvam (2015), industrialization in the sector is essential to deliver industrialized building systems. In this sense, Engineer-to-Order (ETO) systems can be adopted in the construction industry, meaning that customers participate in or contribute to the project and product development process (Gosling and Naim, 2009), enabling the customization of the final product according to customers' preferences. Fundamental challenges in this context regard the balance between standardization and customization, furthermore how to achieve economies of scale within a solution space (Hentschke et al. 2020) and consider building systems limitations (Jansson, Johnsson and Engström, 2014). The adoption of product platforms presents an alternative to companies to cope with that challenge. Product platforms are a set of standardized components that can be reused in different products or within a family of products, according to combination rules (Meyer and Lehnerd, 1997; Robertson and Ulrich, 1998; CIH, 2022). They are typically related to the physical part of products; however, this concept can be extended to repetitive parts of processes, common interfaces, construction technology, or organizational knowledge (CIH, 2022). It is noteworthy, that products are composed by three parts: (i) the standardized, in which one or many components can be the product platform, (ii) the customized, which allows a limited choice within a defined solution space, (iii) the personalized, which enables the a design tailored to specific project requirements, from customers, or site, etc. The balanced combination of those parts in a solution space enables the production of product lines, families, and diverse product variants.

In the construction industry, the adoption of product platforms has been associated with concepts such as mass customization, modularity, and industrialization (Barlow et al., 2003; Schoenwitz et al., 2017; CIH, 2022). However, Styhre and Gluch (2010) highlight that platforms are not easily implemented in the AEC Industry due to the resistance to adopting standardized solutions for project development. Bonev, Wörösch, and Hvam (2015) point out that even though the construction management literature focuses on principles and methods for reducing waste in construction, there is a gap in how to achieve efficient customization of the products. Furthermore, there is a lack of consensus on the concepts of product modularity and platform, and the under consideration of AEC industry particularities for the adoption of these concepts as main barriers for obtaining truthful advances in the field (Rocha, Formoso, Tzortzopoulos, 2015).

This extended abstract discusses the work developed in a project called "CONSTRUA BRASIL", a government initiative for incentivizing industrialization and modernization of the AEC industry in the country. It summarizes part of the work carried out in one of the many goals of the project. The aim of this paper is to present a model for the adoption of product platforms in the AEC industry, focusing on gaining economies of scope and enabling mass customization.

2. Metodology

This paper reports on the initial stages of research that adopts Design Science Research (DSR) as a way to produce knowledge, that focuses on developing an innovative artifact, a model for implementing product platforms in the AEC industry. The research was carried out through the common DSR stages, such as in-depth understanding of the problem, artifact design, and instantiation of an exploratory case study.

Within the government project, the in-depth understanding of the problem was initiated in April 2021. The final report of the Project was delivered in December 2022, with an initial version of a technical standard for the adoption of platforms in construction. This was the starting point for developing the model. During this stage, the solution was refined by the feedback from specialists in a technical consultation group (TCG).

This paper presents a descriptive analysis of the platform strategy adopted by Company A carried out in the exploratory case study to illustrate the model's applicability. Company A is a Brazilian construction company that has a background in prefabrication and has dedicated its products to modular construction (3D and 2D) in the 2000s. With a nationwide action, it has delivered more than a million square meters of construction and ten thousand modules. It is an experienced company with standardized work methodologies, fast assembly, and consistent technical and financial capabilities. The descriptive analysis of the current company A platform strategy allowed the internal refinement of the solution to be applied in the future and contributed to visualizing the utility of the artifact to guide the design and refinement of strategies for the adoption of product platforms in construction. However, it is worth noting that the implementation process was limited to the initial analysis of the strategy. For the research purposes, it was possible to make a better frame of the problem of the company's strategy. The next steps would comprehend the analysis of how to use the model to improve or refine the platform strategy.

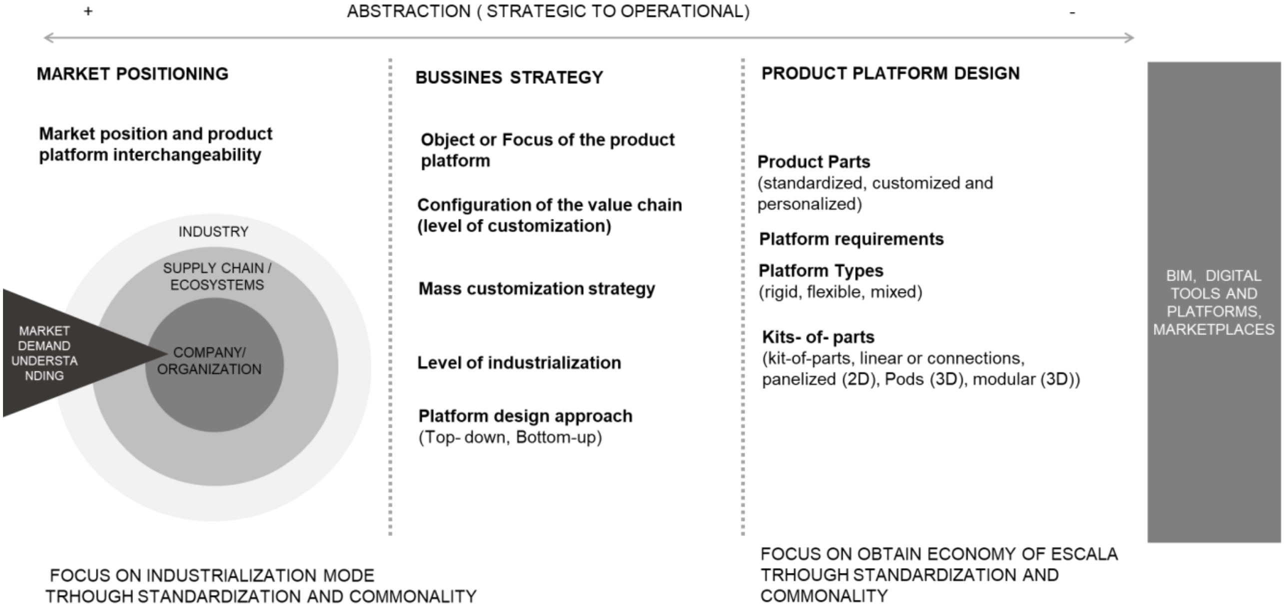
3. Results

3.1 Description of the model

The proposed model aims to guide the implementation of product platforms in construction. It orients companies from market positioning, through the development of a business strategy, to the specific definition and design of product platforms. Recently, in the AEC industry, it is noteworthy that worldwide efforts to embrace product platforms and industrialization to achieve economies of scale through standardization. Nevertheless, the product platform concept is complex to adopt due to its wide applicability and unclear definition. Furthermore, Colombo et al (2020) argue that the adoption of product platforms is a complex process that only pays off when the design solution achieves the preferences of customers, enhancing product attractiveness, and at the same time, increases company productivity. Veenstra et al. 2006 add that the success of product platform adoption depends on the balance between standardized processes and components and the variety of final products. These arguments reinforce the relevance of enabling mass customization through product platforms to generate value for clients.

The model was organized from the most general to the most specific decisions to be made regarding the product platform strategy. It seeks to illustrate the possible scales of adoption, going through a detailed process, and pointing out the need for aligning strategic and operational decisions. It is composed of decision categories, which are ways to classify decisions and support decision-making by decomposing complex problems in a systematic and structured way (Wikner, 2014). Figure 1 portrays the model, which begins by defining decisions related to market positioning, considering market demands and competitors' analysis to define how interchangeable and common their platforms are and with whom. These decisions are related to the model of industrialization adopted by the company as well, which can be open, closed, or semi-open (Gawer, 2014; CIH, 2022; TCNPlus, 2020).

Figure 1: Model for implementing product platforms in construction.



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In the second stage, the company will define its product platform strategy related to its business model by defining the object/ focus of the product platform, level of customization, level of industrialization, platform design approach, and interaction with the mass customization strategy. Initially, the company should define which is the main standardized part of the product to achieve economies of scale, meaning the focus of the product platform, which can be: the building technology, building system, part of the process or service, product module, or piece of knowledge. These parts can be tangible or intangible, regarding physical aspects of the product, such as the chassis or standardized modules; or, not, such as parts of the process, organizational knowledge, among others; respectively. Regarding the value chain configuration and level of customization, platforms are more commonly used in engineer-to-order, make-to-order, and assemble-to-order systems, due to the possibility of customizing final products. These decisions are directly related to the definition of the customer order decoupling point and mass customization strategy (blind reference, 2020).

The third stage of the model is concerned with the definition of the product architecture, the platform, and its interactions with other product parts and the solution space. These decisions regard: the classification of product parts (e.g., into standardized, customized, and personalized parts); identification of product platform requirements (e.g., commonality, quality, interface, configurability, standardization, based on CIH, 2020); definition of platform types (e.g., rigid, flexible, or mixed). When defining the product architecture, the definition of the standardized parts that compose the platform is further detailed and can include more than one product aspect, such as the building systems, chassis, parts of the process, among others, and their combination. As observed in the exploratory case study, each part of the combination will provide different benefits related to its standardization, commonality, and reutilization.

The operationalization of the decisions depends on best practices related to the decisions made in each category (Hentschke et al, 2020) and stage. It is noteworthy that the strategic and operational decisions are connected, and they can change during the detailing process as a natural refinement of the strategy. This connection can be observed among decision categories as well, as mentioned between the decision categories in the business model stage, for example. Finally, in the grey box of the model, BIM and some IT tools, which can support the operationalization of the product platform, were cited; however, they are not part of it.

3.2 Model application in the exploratory study

The application of the model in the exploratory empirical case study analyzed descriptively Company A's product platform strategy, regarding its market positioning, business strategy, and one of its product families. This product family is based on industrialized modules to be assembled on-site.

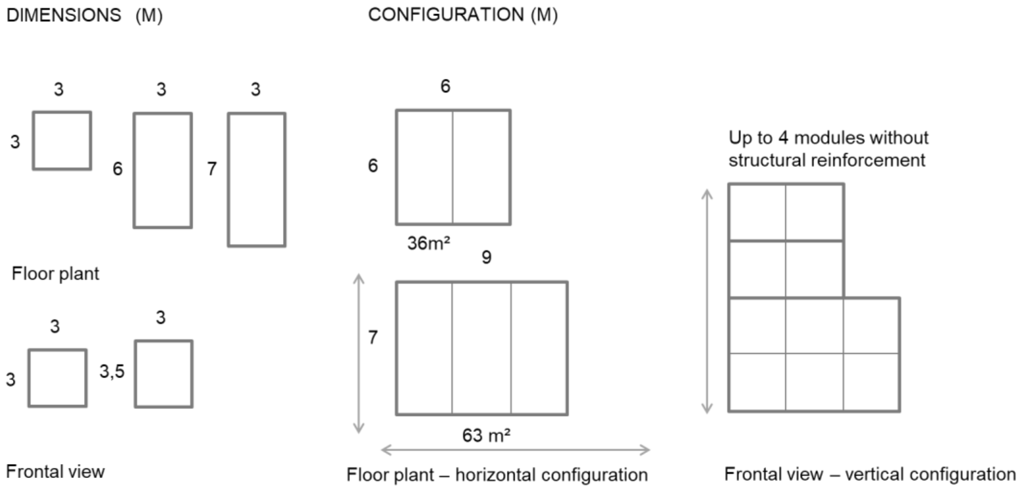
3.2.1Market positioning

The company's ideal is to industrialize as much as possible and reduce activities on the construction site; thus, the modules are taken to the site to be assembled, with minor processes to be finished. Furthermore, the company chose a top-down approach and internalized most of the processes in the product development process, such as project design, production of steel structural chassis and external wall panels, and finally, assembly on-site with all finishings. The building system developed by the company plays a fundamental role in the product platform strategy, since it was born from a market demand, and is aligned with the company's know-how and culture. In summary, the industrialization approach adopted by the company is closed, and its product platform is exclusive .

3.2.2Business strategy

The modular solution of the company was idealized in response to a specific market demand, as an extension to the prefabricated existing solution. This new product line amplified the company's portfolio, enabling it to respond to new market segments, such as education, health, retail, and residential. Within this context, the company adopted a top-down approach to define the product platform, considering the market demand and prior knowledge regarding industrialized systems to propose a new product. Furthermore, the main focus of the platforms in this company is usually the building system, and in this case, it contains some other standardized elements as physical components (e.g., structural chassis, external panels, roofing systems, and MEP kits-of-parts), see figure 2, and parts of the processes.

Figure 2: Configuration possibilities for Company A modules.



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It is noteworthy that the configuration of the value chain of the company is based on ETO to enable increasing levels of customization of the products, which rely on different CODP according to the product family and product variant. For instance, the market segments of health and education present the need for more product variants and customizable attributes, such as layout variations and finishing materials within defined standards. These products are customized to customers' specific needs and preferences within a product family and solution space, enabling the configuration of classrooms, labs, offices, etc. There is the possibility of custom-made buildings in the company as well; however, the lead time and costs are much higher than the other product variants, and they require specific analysis to develop and produce according to the company's capabilities and known processes.

The product family is based on the structural chassis, the core element of the platform, which presents some variations and dimensional limitations fundamental for the configurations of buildings. It also allows flexible combinations, as illustrated in Figure 2. Furthermore, another relevant aspect of the product platform is the external cladding panel made from a light concrete, highly resistant and little explored in the construction industry. It fulfils many relevant functions and is an innovative and technical differential factor of the building system.

3.2.3Product Platform Design

According to CIH (2022) product parts classification, the modules delivered by Company A integrate standardized parts, customizable parts, and personalizable parts, which respectively generate economies of scale, adaptability to different types of use and product variety, and finally, are customized to customers and project-specific requirements. The product can be decomposed according to the examples in Table 1.

It is noticeable that the level of industrialization adopted by the company is of the whole building system, and the standardized parts of the product are described as follows and summarized in Table 1. The modules are composed of a steel structure of beams and columns available in three different lengths (e.g., 3m, 6m, 7m), with 3m width, to facilitate logistics, and two possible heights, 3m or 3,5m, as shown in Figure 2. The roofing system is made of metallic trapezoidal roof tiles. The external wall finishing is made of light concrete cladding panels. The floor system is composed of a secondary steel structure to support and fix concrete slabs. Even though there are other possible compositions for the modules, the aforementioned characteristics and boundaries present high repetition between diverse projects.

The MEP systems rely on a kit-of-parts strategy, which equalizes flexibility and efficiency, guarantees quality control, strengthens the value chain, and facilitates crew training. For instance, in educational buildings where the classroom is a repetitive piece of design, the electrical and hydraulic kits-of-parts can be the same and just mirrored as the configuration on site.

Table 2: Summary of the application of the model in Company A

PRODUCT PARTS	EXAMPLES OBSERVED IN Company A MODULES
STANDARDIZED	Chassis structural elements (e.g. , beams and columns), support elements for floors, external wall panels, and roofing system.
CUSTOMIZABLE	Colors of the light concrete of the external wall panels (3 colors) and of the roofing tiles (e.g., white, gray, or painted); materials for the internal wall (plasterboard or fiber cement boards); color and materials of windows and doors; floor finishings (e.g., ceramic, vinyl, or fair-faced concrete); among others.
PERSONALIZABLE	Internal walls layout; special facade finishing elements (e.g., brise-soleil, wood paneling, glass), infrastructure systems, and final roofing; and configuration of changes and extensions.

Font: The authors

The internal wall systems and lining are multilayered, facilitating customization according to customers' preferences, including their finishes, which are made of fiberglass insulation, oriented strand board (OSB), and plasterboard. Other personalizable aspects of the project, not mentioned in Table 1, include the positioning and window sizes, which are allocated in the external wall panel molds according to design specifications.

4. Discussion

The model application on the empirical study enabled understanding the platform strategy adopted by Company A. It also allowed the identification of the main challenges to balance customization and standardization for industrialized systems aligned with the company's business strategy. As evidenced, the product platform enabled scale gains; meanwhile, the customized and personalized parts guarantee the flexibility needed to meet customers' needs and preferences. These contributions are aligned with the perspective of Bonev, Wörösch, and Hvam (2015), who state the relevance of product platforms for defining clear limits between commonality and customization, and in rethinking the processes and costing approaches for industrialized construction. Furthermore, the research reinforces Jansson, Johnsson, and Engström (2014) argument that the adoption of product platforms in construction requires a change of mentality regarding the preconception that there is a loss of project singularity in addition to standardization and operational efficiency. In the empirical study, Company A amplified their portfolio and offers a large solution space within which customers can configure their products with controlled costs and lead times; however, the fully personalized solutions have proved to be economically unfeasible. Thus, there is a need for clear rules of customization and personalization to enable the delivery of an adequate product through a flexible product and process that is economically feasible.

5. Final considerations

The model illustrates concepts and relationships that facilitate the understanding of the use of product platforms in construction and can support the design of strategies for implementing product platforms or refining existing ones, based on decisions to be made from market positioning to operationalization of the product families.

The empirical study presents some limitations in terms of being a partial implementation, mostly through the description of an existing strategy; and also, the high level of maturity of the company using industrialized building systems made it easier, newer companies may need some adaptations for full implementation. Nevertheless, Company A has benefited from the model instantiation, since it enabled the identification of its product platform strategy, and further understanding of its product families, and clarified the rules of combination. Moreover, it was possible to map the product platform parts, interfaces, customizable attributes, and solution spaces through the decision categories proposed in the model. Mapping the parts provides evidence of how the company reduces waste in its production system, operational costs, and lead time, and maintains design flexibility.

Foreseen further research opportunities include: the full implementation of the model and follow up of its results; test the model in other products and market segment, for instance that require a higher customization level such as high end residential; identification of related best practices, that enable the operationalization of decisions and problem-solving; proposition of new technical standards and guidelines for the adoption of platforms in construction, to incentivize industrialization; etc.

Acknowledgements

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BIBLIOMETRIC MAPPING OF PREFABRICATED WALL PANEL DESIGN

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ABSTRACT

Prefabricated buildings are increasingly prominent in the construction industry due to their efficiency, sustainability, and cost-effectiveness. This study systematically maps the research landscape of wall panel design in prefabricated buildings through bibliometric analysis. Employing a systematic literature review (SLR) methodology adhering to the PRISMA 2020 guidelines, we retrieved and analyzed 542 publications from 2015 to 2025 from Web of Science, Scopus, and Google Scholar. Using VOSviewer and Connected Papers, keyword co-occurrence network visualization and overlay visualization were conducted to identify key themes, clusters, and temporal trends. The results revealed four dominant clusters centered on sustainability, structural performance, and digital design technologies, with emerging focus on circular economy, BIM integration, and AI optimization. This mapping provides strategic insights for advancing prefabricated wall panel innovation.

Keywords: Bibliometric analysis; Wall panel design; Cluster analysis; Trend mapping; VOSviewer

1. Introduction

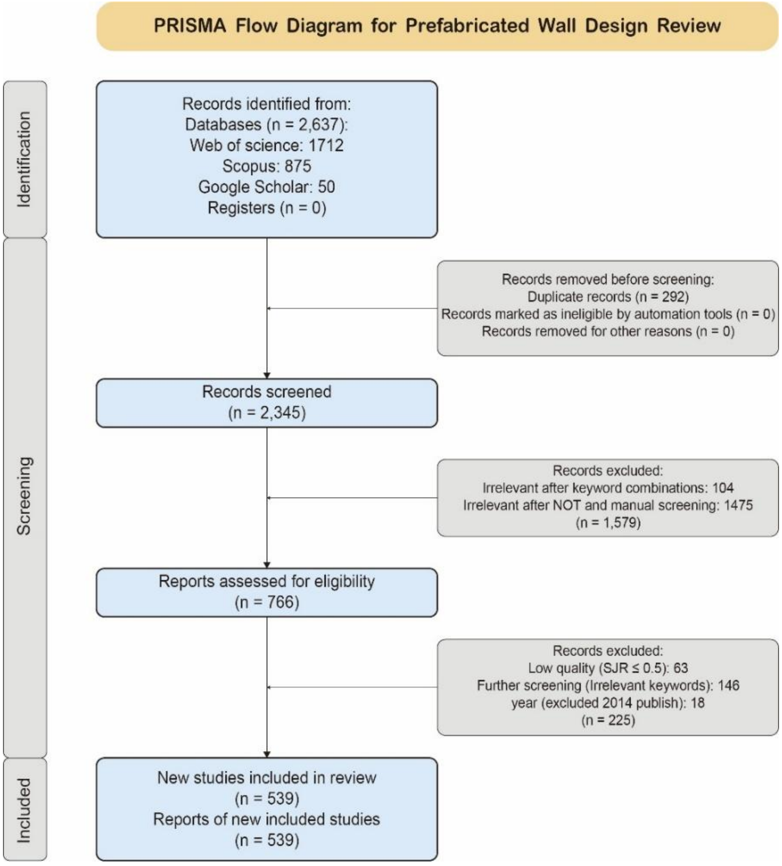
The construction sector is undergoing a paradigm shift towards prefabricated and modular building systems, driven by the need for faster project delivery, reduced environmental impact, and improved quality control (Smith, 2010). Prefabricated wall panels, as core components of off-site construction, integrate materials like concrete, timber, and composites, often incorporating features such as insulation and fire resistance (Li et al., 2014). However, the design domain remains fragmented across architecture, engineering, and materials science. Bibliometric analysis offers a quantitative perspective to synthesize this knowledge base, revealing patterns in publications and thematic evolution (Chen, 2017). This method has been applied in construction research to map sustainable building trends (Darko et al., 2019).

The research objectives are twofold: first, to systematically review and screen relevant literature from 2015 onwards; second, to visualize keyword networks, clusters, and temporal trends using VOSviewer and Connected Papers. By addressing these, this study provides an integrated overview of the field. The paper is structured as follows: Section 2 details the methodology, Section 3 presents results and discussion, and Section 4 summarizes final considerations.

2. Methodology

This study adopts a systematic literature review (SLR) approach following PRISMA 2020 guidelines (Page et al., 2021) to analyze prefabricated wall panel design research. The process includes literature retrieval, data integration, screening, quality assessment, and visualization, as summarized in Figure 1 (PRISMA flow diagram).

Figure 1: PRISMA Flow Diagram



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Literature was retrieved on July 29, 2025, from Web of Science (WoS), Scopus, and Google Scholar using the keyword string: ("prefabricated" OR "precast" OR "modular" OR "off-site constructed" OR "industrialized building") AND ("wall" OR "wall panel" OR "wall system" OR "facade panel" OR "curtain wall") AND ("design" OR "architecture" OR "construction" OR "fabrication" OR "manufacturing"). Constraints: 2015-2025, English, peer-reviewed articles/conferences/reviews. Initial retrieval: 2637 publications (see Table 1 for database summary).

Table 1: Summary of Literature Retrieval

Database	Initial Results	Advantages/Limitations
Web of Science	542	High-impact; limited refinement
Scopus	1895	Keyword exclusion; interdisciplinary
Google Scholar	200	Open-access; manual review needed

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Data were integrated in EndNote 21, deduplicated (2345 unique), screened (excluding irrelevant topics like seismic/shear, yielding 766), and quality-assessed (SJR >0.5, removing 63 low-impact; final: 542). Visualization used VOSviewer for keyword co-occurrence and overlay networks (min. occurrences: 10) and Connected Papers with seed article (Huuhka et al., 2015)

3. RESULTS AND DISCUSSION

Analysis of 542 publications reveals evolving trends. Publication output grew from 20 in 2015 to 105 in 2024 (CAGR ~20.3%), with citations peaking recently, indicating maturing impact (Figure 2).

Keyword co-occurrence (75 keywords, 1125 links, density 0.405) forms four clusters: (1) Performance and Design (e.g., "performance", link strength 108); (2) Building Systems (e.g., "architectural design", 78); (3) Materials and Concrete (e.g., "precast concrete", 187); (4) Sustainability and Manufacturing (e.g., "prefabrication", 103) (Figure 3; Table 2). Temporal overlay shows shifts from materials (pre-2020) to sustainability/digitalization (post-2022), with "circular economy" emerging (avg. year 2023.2).

Figure 3: Keyword Co-occurrence Network

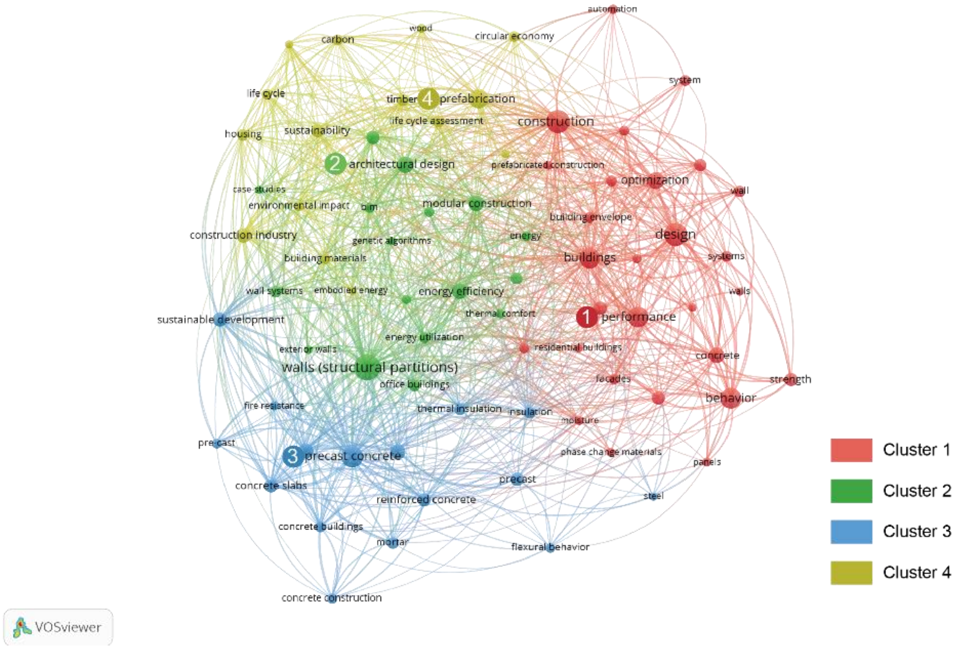

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Table 2: Cluster Summary

Cluster	Center Keyword	Link Strength	Focus
1	Performance	108	Innovation
2	Architectural Design	78	Frameworks
3	Precast Concrete	187	Engineering
4	Prefabrication	103	Sustainability

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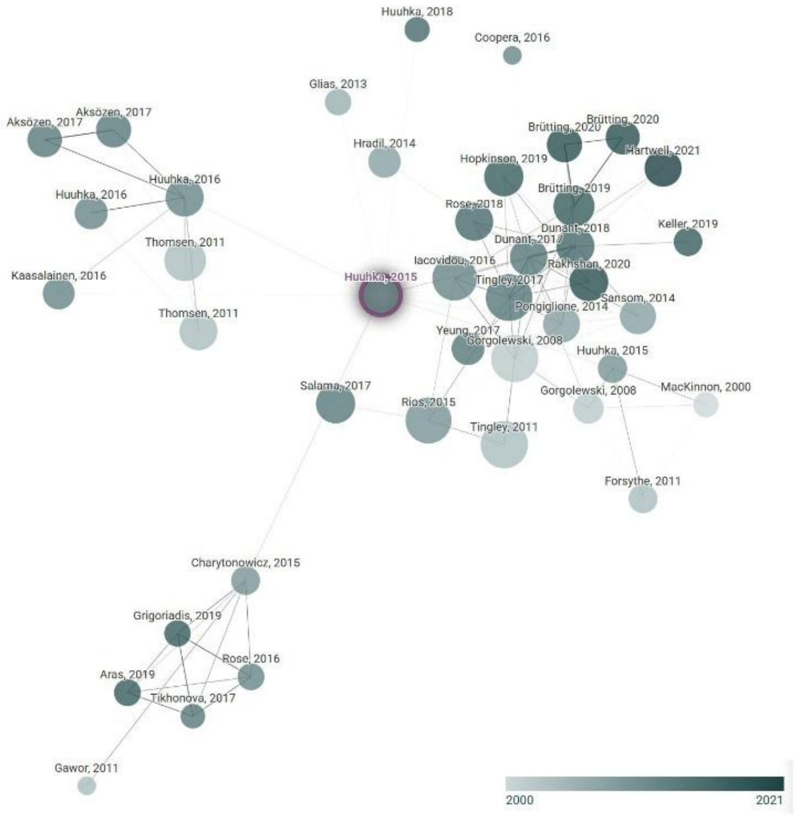
The similarity network (Figure 4) confirms cohesion around reuse/sustainability, with clusters on deconstruction and materials performance, bridging foundational to innovative themes. These visualizations highlight interdisciplinary connections and a green transformation trend (Wuni et al., 2019).

Figure 4: Similarity Network Graph



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4. Final Considerations

This bibliometric mapping synthesizes the prefabricated wall panel design landscape, revealing clusters and trends from materials to sustainability. Contributions include a quantitative overview aiding scholars and practitioners. Limitations: English-only literature and parameter thresholds may miss emerging terms.

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HIERARCHICAL PRODUCT VIEWS TO SUPPORT PRODUCT PLATFORM DEVELOPMENT IN INDUSTRIALIZED HOUSE-BUILDING

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ABSTRACT

Industrialized House-Building (IHB) companies offering single-family houses often operate with extensive catalogs based on integral architecture, typically lacking flexibility, disregarding manufacturing constraints, and leading to noncompetitive prices and quality issues. Mass Customization (MC) and related concepts such as product platforms, modularity, and product families are increasingly being adopted in different industries to enable reuse of solutions across product variants, allowing front-end variety while keeping some degree of back-end commonality. Product platforms can serve as an integration mechanism by clarifying product development boundaries. However, successful implementation depends on aligning MC areas - Customer Integration, Product Design, and Operations Management. Challenges include fragmented views, solutions shaped by single perspectives, inconsistent terminologies, and misaligned understandings of core concepts. A Design Science Research methodological approach guided an eleven-month empirical study carried out with two partner companies in the United States and Mexico during their transition from a conventional catalog to a product platform strategy. This paper explores how hierarchical product views can support the definition and development of product platforms in the IHB context. Findings suggest that hierarchical product views help teams visualize trade-offs, identify appropriate levels of granularity, foster a common language across areas, and build shared understanding and adoption of MC-related concepts.

Keywords: Product Platform; Product Platform Development; Mass Customization; Hierarchical Product Views; Industrialized House-Building.

1. Introduction

The Mass Customization (MC) strategy and continuous improvement models have enabled firms to overcome the traditional trade-off between scale with more standardized products at low cost versus highly-differentiated products at high costs (Pine et al., 1993). More recently, MC has emerged as a strategy in house-building projects to improve value delivery (Noguchi, 2003; Yashiro, 2014) and address specific requirements of customers while maintaining costs and delivery time similar to mass production (Pine, 1993; Hart, 1995; Tseng & Jiao, 1996; Da Silveira et al., 2001). MC success relies on integrating decisions from three areas: Customer Integration, Product Design, and Operations Management (Jiao & Tseng, 1999; Ferguson et al., 2014; Schoenwitz et al., 2017). Managing and integrating the diverse information of those areas (Larsen et al., 2019) requires a collaborative, multidisciplinary approach from early design stages to define a finite Solution Space that incorporates both customer and operational requirements (Piller, 2004; Ferguson et al., 2014). Unlike traditional personalization, MC avoids reinventing products and processes for each customer (Piller, 2004).

The reuse of solutions across products (Brege et al., 2013) enables a shift from extensive catalogs of unique products based on an integral architecture approach and low flexibility (Sanchez, 1999) to products more suitable for the IHB context. Concepts such as product platforms, modularity, and product families (Salvador et al., 2009; Khalili-Araghi & Kolarevic, 2018) support this transition, offering front-end variety while keeping some degree of back-end commonality (Eriksson & Emilsson, 2019). However, they require significant product development effort up-front (Bonev et al., 2015) and early design stages' multidisciplinary integration (Jansson, 2013), supported by shared language and structure to balance the business model trade-offs through iterative problem solving (Robertson & Ulrich, 1998).

Fragmentation among IHB stakeholders –developers, designers, manufacturers, general contractors, and regulators— often leads to solutions shaped by single perspectives (Rocha, 2011), differing product views (Robertson & Ulrich, 1998; Tseng & Jiao, 2001; Hvam et al., 2008), and inconsistent terminologies to express their requirements. This highlights the need for product- and process structures capable of integrating and managing information while clarifying interrelationships (Jiao & Zhang, 2005; Hvam et al., 2008). Additionally, companies often overlook the cultural shift required to recognize customers as co-creators of value within an MC strategy (Piller, 2004).

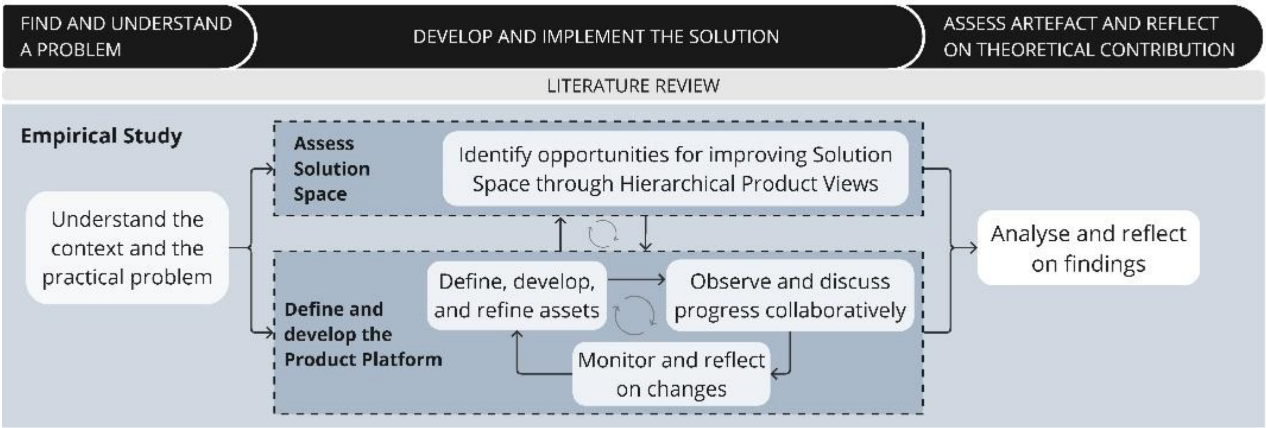
Product platforms have been adopted to address some of these challenges by supporting integration across diverse stakeholder perspectives, improving communication, and clarifying product development boundaries (Jiao & Tseng, 1999). However, their development demands more than technical coordination. It requires a cultural shift toward shared understanding of concepts and iterative, multidisciplinary decision-making. Hierarchical product views, which represent product architecture across different levels of granularity (Tseng & Jiao, 1996), are used in this study as a mechanism to support this transition by helping teams to visualize trade-offs, understand the appropriate levels, and foster a common language across areas (Tseng & Jiao, 1996). The aim of this paper is to explore how hierarchical product views can support the definition and development of product platforms in the IHB context. This study distinguishes itself from existing research on product platforms and hierarchical product views (Jiao, Zhang, 2005; Hvam et al., 2008; Jensen et al., 2009; Wikberg et al., 2014; Lennartsson et al., 2023) by discussing the role of these hierarchical views in fostering collaboration and building shared knowledge and values among stakeholders during the transition from conventional catalogs toward product platform development.

2. Research Method

This study adopted the Design Science Research (DSR) methodological approach, which aims to develop solution concepts, or artefacts, to address complex and relevant field problems (Voordijk, 2009). The empirical study was conducted in two IHB partner companies: (1) Company X is a manufacturing firm based in the U.S. and recently relocated its main production facilities to Mexico; (2) Company Z is a product developer, seller and real estate developer. Company Z approached Company X to manufacture their catalog of single-family houses targeting medium- to high-end income customers. Company X required catalog reduction and reconfiguration to fit the IHB context, leading to a collaborative, multidisciplinary process between the two companies. This process was supported by the first author of this paper.

The study was conducted during the researcher's split Ph.D. period in the U.S., later continued remotely from Brazil through regular online meetings and an immersive in-person workshop in Mexico. Figure 1 outlines the research design, based on DSR phases (Kasanen et al.,1993; Lukka, 2003).

Figure 1: Research Design.



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Multiple sources of evidence were used: 28 participant observations, 9 informal meetings, 1 formal meeting, 1 semi-structured and 1 open-ended interview, 1 direct and 1 indirect observation, 1 site visit with a week-long immersive workshop, and analysis of 11 documents. These activities involved over 15 representatives and 87 hours of direct engagement. The study lasted eleven months.

The first research phase, "Find and understand a problem," carried out by means of the research activity "Understand the context and the practical problem" (Figure 1), began with three informal meetings with Company X's Co-founder/CEO. This was followed by a joint strategy meeting between both companies involving multiple representatives, which marked the beginning of weekly collaborative development sessions. The second research phase, "Develop and implement the solution", was carried out through iterative learning cycles across two research activities. The first, "Assess Solution Space", involved a set of analyses led by the researcher to help the companies understand and apply MC-related concepts. The assessments were framed as scenarios to "Identify opportunities for improving Solution Space through Hierarchical Product Views". The findings were presented and discussed collaboratively during the weekly meetings and shared with additional stakeholders. The second, "Define and develop the Product Platform" involved (i) Define, develop, and refine assets; (ii) Observe and discuss progress collaboratively; and (iii) Monitor and reflect on changes.

This iterative process was unfolded across three distinct periods: (a) weekly collaborative development meetings (online), initially planned for six weeks but extended to seventeen, and involving a core group from both companies; (b) one week-long immersive workshop (at Company X's manufacturing facility in Mexico) that resulted in the Product Platform Guidelines Document, consolidating key decisions and strategies; and (c) post-workshop weekly collaborative development meetings (online) that focused on testing and detailing the product platform solutions through continuous iteration.

3. Results

3.1 Understand the context and the practical problem

Company Z's original catalog comprised 20 single- and two-story houses (65 - 367 m^2), developed as one-of-a-kind products without clear market segmentation. The limited understanding and adoption of MC-related concepts meant that each product had to be designed and detailed from scratch, limiting the benefits of operating in an IHB context. This led to high design costs, low reuse of solutions across product variants, lack of commonality and standardization, and limited economies of scope.

In response to Company X's request to adapt the catalog to the IHB context, two initiatives were launched in parallel. First, a joint team from both companies started a series of weekly collaborative meetings that began by defining the scope and the participants, discussing the business model's goals, and establishing the working structure. A list of "major topics" was collaboratively defined, guided technical discussions, and progressively evolved into the Product Platform Document. A key issue was defining the ideal module sizes, considering its influence on the building system and on transportation constraints and costs. Second, two senior architects from Company Z internally proposed reducing the 'wide' catalog to seven best-selling houses by standardizing them as much as possible.

3.2 Assess Solution Space

The researcher assessed both the wide and the reduced catalogs to identify opportunities for improving the solution space and to reach a shared understanding of MC-related concepts. The original catalog included twenty one-of-a-kind houses comprising 63 modules with 25 different lengths and 4 widths, none reused across products. The teams' understanding of the "modularity" concept was limited to the volume that encompassed the maximum transportation load. Customization was limited to two finishing packages.

The reduced proposal simplified the offer to seven one-of-a-kind houses composed of 13 modules, but maintained many of the same issues observed in the original extensive catalog. Additionally, the selection of the products was done with no clear understanding of the target market or customers' needs. This shift from an overly extensive to a highly restrictive offering failed to meet the goals of standardization, commonality, and customization, highlighting the need for a deeper redefinition of the solution space.

With a strong participation of the first author of this paper, products were broken down into different hierarchical levels or levels of granularity. A set of seven submodules (rooms or combination of rooms) with potential for repetition or reuse across house models was proposed. A visual and dimensional analysis was conducted to evaluate differences in layout, length, internal and external wall configurations, window and door positions, and closet wall placement. Despite spatial similarities, submodules varied unnecessarily, adding complexity without adding customer value. To address this, the researcher proposed reducing unnecessary variation by standardizing modules with fixed dimensions and positions of opening that could be used or not depending on the configuration. This logic supported the proposition of product families, e.g., maintaining a fixed platform (social area) and varying bedrooms or the garage. It exemplified the possibility of addressing different customer profiles by means of the same set of submodules, enhanced customization and product commonality, and enabling smaller batch sizes, thereby supporting continuous improvement. However, the reduction of the modules' sizes also implied more interfaces and potential redundancies or higher costs. These trade-offs led the researcher to raise a set of critical questions to the team with the aim of deepening the discussion around concepts, such as: "What is the customer demand and the target market where we are trying to sell houses? How many options are actually necessary? What is the best module size for the design? Manufacturer? Customer? What are the benefits and challenges of adopting the "module" or "submodules" size? Is the redundancy cost of the submodules worth it?"

The impact of this analysis was immediate on the working group and initiated a shift away from the prevailing mindset of integral architecture. Although the initial reaction from the architects was defensive, it opened space for reflection and change. The approach challenged their entire way of thinking, designing, and structuring the products. According to the co-founder and CEO of Company Z, the message aligned with what he had been trying to communicate to the team for years but he had not been fully understood.

Following the researcher's presentation, a multidisciplinary team started iterative discussions about the building system and the ideal module size to be adopted. Most of their questions could not be fully answered at the start, but would be later in the cours of the process. Despite the researcher's and Company X's effort to incorporate customer demand as a key input, Company Z maintained the traditional separation between design and marketing functions, common in the IHB sector. The team agreed to work with volumetric submodules with the maximum of 4 to 6 meters in length and a fixed width of 4.27 meters, assembled into modules in the factory and connected onsite into a complete house.

The two senior architects then redesigned the proposal using 16 submodules with standardized width/height and nine different lengths. Company X's Co-founder/CEO questioned the architects if they felt constrained, and they stated: "No, we did not exactly feel constrained. It was quite an interesting exercise because we needed to learn a new way of thinking about the design process and the product. And it was quite fun, similar to a game." As the submodule logic proved viable, new questions emerged about what constitutes variation and how to manage minor differences within submodules. The team also began exploring structural options and interfaces (e.g., submodule-submodule, module-foundation), openings, roofing, MEP, HVAC, temporary waterproofing, façade, and interior finishing, and redundancies. Recognizing the complexity of these decisions, Company X proposed to host an in-person, week-long immersive workshop in Mexico.

3.3 Define and Develop the Product Platform (Workshop)

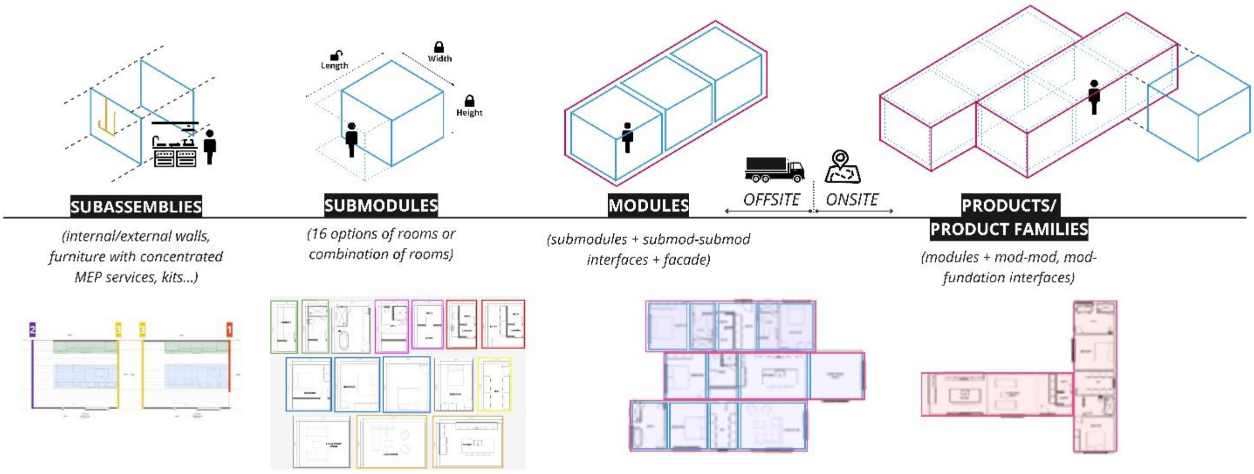
The workshop brought together eight participants from seven countries, including the researcher. The aim was to create an iterative, collaborative foundation for decision-making across MC areas, and to accelerate decision-making regarding the product platform assets and the building system. The researcher led the kickoff by proposing and facilitating alignment around a list of key topics, which evolved throughout the week and later structured the product platform document. There were no marketing or customer integration roles present. The researcher addressed this from a theoretical standpoint, guiding strategic reflections on the business model's main goal, target customer, and cost objectives. The researcher (first author) also ensured that the team remained aware of the MC-related concepts during the ongoing development of solutions. Her neutral role helped balance trade-offs and align design, technical decisions with broader strategic goals, envisioning a resilient product platform capable of accommodating future changes.

Starting from the 16 proposed submodules, the in-person collaborative environment sparked rapid progress, as expressed by the VP of Operations: “We advanced more in two hours than in two years. We should have done it before.” Key topics included: balloon vs. platform framing, wall redundancies, roof and floor standardization, wall compositions, HVAC, interfaces and joints, customization options, and future two-story development. Technical simulations and cost analyses of multiple alternatives were developed in parallel with discussions, supporting real-time decision-making.

On the last day, discussions turned to implementation strategies, including submodule assembly, manufacturing flow, and prototyping. Business model implications also emerged, particularly the possibility of shifting from a B2C to a B2B approach using submodules to develop co-branded catalogs. To support this, the researcher (first author) proposed scenarios of product families based on submodule combinations and suggested ways of presenting the solution space in alignment with those strategies. A second analysis presented by the researcher focused on opportunities for standardizing wet areas. By classifying and comparing module widths, types of wet areas (kitchen, bathroom, and laundry), formats (volumetric/pod; non-volumetric/panelized and furniture; and furniture), layout dimensions, and positions of openings, the analysis provoked strategic questions on how to build rules and manage minor variations. Rather than offering solutions, it encouraged reflection on product development through the lens of MC-related principles and concepts.

Following the workshop, teams finalized technical contents and presented the product platform document to the two senior architects and a broader group of stakeholders, including top managers, investors and consultants. Subsequent work focused on detailing submodules and testing the feasibility of key decisions. Then, the architects and the director of DfMA required the researcher (first author) a new assessment of the final set of submodules to analyze product variation and commonality opportunities from a MC perspective.

Figure 2: Hierarchical product views adopted in this study with corresponding examples.



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3.4 Assess Solution Space (Post-Workshop)

The researchers identified a gap in how the team was approaching modularity and commonality concepts, which moved from the module down to-, but remained centered, on the submodule level.

To expand this perspective, products were broken down into multiple levels of granularity. The sixteen submodules were decomposed into a set of elements such as internal and external walls (single/double), furniture and walls with concentrated MEP services (mechanical, electrical, and plumbing). The presentation highlighted the potential of repetition of these recurring subassemblies across multiple submodule types. This perspective encouraged the team to reflect on how modularity could serve and be perceived and leveraged by different stakeholders. For B2C customers, the focus lies on product family and customization options; for B2B customers, they might configure their own product families by combining predefined submodules; and for manufacturers, opportunities for reuse and standardization exist not only at the module, submodule, and interface levels, but also within recurring walls, kits, furniture, opening patterns, and processes. Figure 2 illustrates the hierarchical product views adopted in this study, with corresponding examples of solutions developed during the product platform development process.

This stage of the study marked a maturing understanding of MC concepts, evolving from fixed modules to a hierarchical understanding of the product system. This phase laid the foundation for a second in-person workshop in Mexico, this time involving designers and sales managers who were facing difficulties adapting detailing practices to the concepts and to the IHB context. The detailing phase of the product platform assets and its submodules extended over six months, during which the decision-making process became increasingly technical and specialized, and the researchers' involvement gradually decreased.

4. DISCUSSION AND CONCLUSION

This paper discussed how the assessment of the solution space through hierarchical product views can support the development of a product platform when transitioning from a traditional catalog to a mass-customized modular housing strategy. Conducted in close collaboration with multidisciplinary team members from two companies, the study showed both opportunities and challenges in aligning stakeholders, concepts, and decision-making across the MC areas. The results can be summarized and categorized into five topics:

- **Iterative process between "Solution Space Assessment" and "Product Platform Development"** effectively aligned perspectives across companies, stakeholders, and MC areas. Beyond technical decisions, the success of a product platform depends on developing a shared understanding of MC-related concepts, requirements, and constraints among practitioners with distinct roles and priorities.
- **Hierarchical product views allowed the teams to progressively deepen their understanding of MC-related concepts**, moving from higher (products, modules) to lower (submodules, interfaces, subassemblies) levels of granularity. This approach revealed opportunities for standardization and reuse of solutions at multiple levels, enabling product platform resilience and adaptability as new information and constraints emerged. Interfaces emerged as critical, and grounding the analysis in the current catalog helped the team to deeply connect with the concepts. The building system, design strategies, and product platform must evolve together, enabling the postponement of decisions on the granularity level as maturity increases. Moreover, decomposing products into hierarchical levels made it possible to represent and align the perspectives of different stakeholders.
- **Product platform development depends on collaborative routines.** Regular online multidisciplinary meetings and immersive workshops were key to accelerating decisions, building trust, and enhancing the teams' ability to resolve trade-offs in geographically dispersed teams. Documenting the product platform enhanced shared understanding and exposed unresolved issues and blind spots that could lead to quality problems or rework.

Grounding decisions in MC-related concepts allowed the companies to build a robust structure capable of continuous improvement and responsiveness to market shifts (e.g., B2B opportunities).

- **External facilitation** by the researcher (first author) ensured that strategic goals (e.g., business model, target market, customer needs) and MC-related concepts remained visible, understood and addressed during technical discussions and trade-off decisions. The facilitator bridged perspectives and reminded the team that solutions should be pursued from a collective- rather than individual viewpoint.
- **Transitioning from integral architecture to MC strategy takes time** and requires mindset changes, shared knowledge, and aligned values among companies and MC areas. This process is non-linear, involving multiple learning cycles, iterative decision-making, and movement back and forth across hierarchical product levels as team maturity grows and solutions evolve, as many answers are not available at the initial development stages. Clear business model goals, target cost, and target market definitions are essential to guide decisions within strategic boundaries.

The following steps of this investigation involve the development of prescriptive knowledge to support companies transitioning from traditional catalogs based on integral architecture toward product platform development grounded in MC-related concepts. Finally, suggestions for further research include the integration of customer demand- and requirement data, as well as the study of indicators and metrics to assess the level of commonality among products.

Acknowledgement

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CHAPTER 7

HUMAN CENTRIC DESIGN

NEIGHBORHOOD GREEN CIRCLES: A SUSTAINABLE COMMUNITY-DRIVEN URBAN FARMING INITIATIVE TO PLANT THE EMIRATES

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ABSTRACT

This study explores how underutilized traffic infrastructure—specifically neighborhood roundabouts—can be transformed into edible landscapes that support social sustainability, food resilience, and participatory governance in hyper-arid, car-oriented contexts. Focusing on three districts in Al Ain, United Arab Emirates, the research combines spatial mapping, resident surveys (n = 107), and interviews with local community farmers to evaluate the feasibility and lived experience of roundabout-based urban agriculture. The findings reveal that while residents strongly associate edible landscapes with social cohesion, cultural identity, and ecological benefit, successful implementation depends on three critical social sustainability domains: proximity, productive land use, community participation, and municipal integration. The study introduces a design-and-governance framework that operationalizes these domains, offering a transferable planning model for cities across the Gulf region. By foregrounding everyday spaces and community co-stewardship, the Green Circles initiative complements national sustainability campaigns such as Plant the Emirates, aligned with Sustainable Development Goal 11 (Sustainable Cities and Communities), which often prioritize flagship greening over neighborhood-scale engagement. The study contributes to urban agriculture literature by reframing ornamental infrastructure as socially embedded civic space and by advancing a grounded model for sustainable, inclusive transformation in the Gulf. Findings also inform future practices and policies for scaling community-driven greening in arid-region cities worldwide.

Keywords: Sustainable urban farming, Urban agriculture and placemaking, Community gardens, Edible landscapes, Food security and green infrastructure.

1. Introduction

Cities in arid regions such as the United Arab Emirates (UAE) confront intensifying pressures associated with climate change, food insecurity, ecological degradation, and weakening social cohesion. Within this context, urban agriculture is increasingly framed in the academic literature as a multi-scalar mechanism capable of mediating these challenges (Degefa et al., 2021; Jung & Awad, 2023; Alawadi, 2025). A growing body of Scopus-indexed scholarship now interrogates Emirati practice from diverse disciplinary angles: household surveys quantify the dietary contribution of home gardens (Degefa et al., 2021); scenario-modelling work tests the land-use efficiency of *foodscape* in Al Ain (Alam & Gabriel-Neumann, 2024); ethnographic studies document resident-led cultivation in Abu Dhabi housing clusters (Galal Ahmed et al., 2024); decision-analytic research critiques the planning priorities of Sharjah Sustainable City (Jung & Awad, 2023); agronomic experiments evaluate wastewater-irrigated crops as a climate-adaptive strategy (Al Hamedi et al., 2023): and Anabtawi & Bleibleh assess the resilience of public markets as critical spaces for food access and social sustainability in the UAE (2025). Collectively, these studies illuminate both the promise and the present limitations of urban farming in a hyper-arid context—chiefly fragmented governance, stringent water constraints, and an over-reliance on capital-intensive technology.

Notwithstanding these scholarly advances, a structural gap endures between the UAE's flagship agri-tech ventures and the quotidian spaces of residential neighborhoods. Smaller community-driven models can reinforce place attachment, foster intergenerational knowledge exchange, and generate public-health co-benefits—outcomes seldom delivered by large-scale, technologically sophisticated projects alone. Al Ain, despite its horticultural heritage and distinctive network of roundabouts, still lacks planning frameworks that embed edible landscapes into everyday neighborhood life.

Addressing this gap, the "Neighborhood Green Circles" initiative proposes converting under-utilized secondary roundabouts into community-managed edible gardens. Aligned with the national "Plant the Emirates" campaign and Sustainable Development Goal 11 (Sustainable Cities and Communities), the initiative reimagines vehicular infrastructure as productive, socially vibrant, and climate-resilient public space. International precedents—from Seattle's traffic-circle gardens to Barcelona's super-blocks—demonstrate the feasibility of such transformations, yet deploying the model in Al Ain's arid, car-centric context introduces fresh design, governance, and environmental challenges.

Roundabouts in Al Ain, originally engineered for traffic flow and ornamentation, are strategically dispersed, highly visible, and spatially central to neighborhood life. Repurposed as edible landscapes, they can provide micro-climatic cooling, carbon sequestration, and biodiversity support while simultaneously offering shaded meeting points, locally grown produce, and culturally resonant planting palettes. By foregrounding participatory governance, climate-adaptive design, and low-tech stewardship practices, the Green Circles model complements—rather than competes with—ongoing agri-tech investments, filling a critical void in UAE urban-agriculture discourse by centering everyday citizenship, inclusivity, and placemaking. Grounded in mixed-method empirical work—including community surveys, spatial mapping, and qualitative interviews with neighborhood farmers—this paper articulates a replicable framework for edible roundabouts as catalysts for sustainable, culturally embedded, and socially equitable urban futures in the UAE.

Despite the emergent Emirati scholarship, no study has yet provided empirical evidence on how the micro-conversion of neighborhood roundabouts into edible landscapes mediates the intertwined goals of walkability, food security, and social cohesion in a hyper-arid, car-oriented context. This research addresses that gap by integrating spatial analytics with lived community experience to evaluate the viability and impact of roundabout-based urban farming. In doing so, it produces a transferable design-and-governance framework that municipal planners, landscape architects, and community organizations can adapt when implementing edible roundabouts in other hyper-arid, automobile-dependent contexts.

Accordingly, the investigation is anchored by three core questions that bridge empirical observation with design practice. First, how do neighborhood spatial form, resident perceptions, and local governance interact to shape both the feasibility and the sustained stewardship of edible roundabouts in Al Ain? Second, to what extend does converting secondary neighborhood roundabouts into community-managed urban farms measurably improve walkability, strengthen social cohesion, and moderate micro-climatic stress relative to existing baseline conditions? Third, how can the empirical insights from these neighborhoods be synthesized into a transferable design-and-governance framework, and what evidence demonstrates the framework's robustness across contrasting urban morphologies?

2. Literature Review and Theoretical Framework

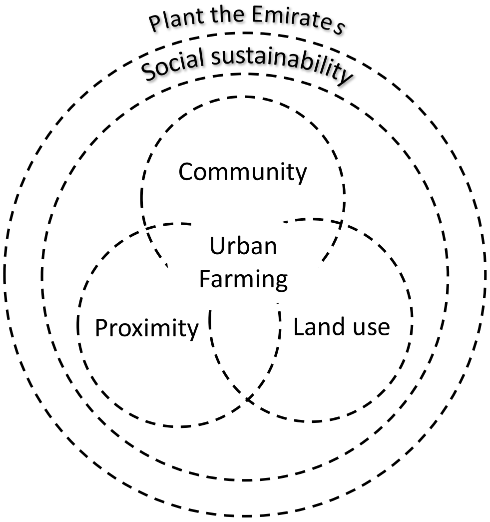
Scholarship on urban agriculture has progressed from quantifying yields toward acknowledging its multifunctionality. Foundational syntheses—such as Mougeot's Growing Cities, Growing Food (2005) and Taylor and Lovell's (2014) narrative review—demonstrate that edible landscapes can simultaneously deliver nutritional security, biodiversity support, and social cohesion. Empirical evidence from the UAE corroborates these claims: wastewater-irrigation experiments in Abu Dhabi achieved significant water-use efficiency while maintaining marketable yields (Al Hamedi et al., 2023), and agent-based simulations of integrated foodscape in Al Ain project a 17 % rise in neighborhood self-sufficiency without breaching grey-water budgets (Alam & Gabriel-Neumann, 2024). These studies justify treating urban agriculture as essential socio-ecological infrastructure.

Concurrently, placemaking scholarship underscores how purposeful re-design of ordinary public spaces fosters community identity and long-term stewardship. Hou et al.'s (2009) ethnography of Seattle's community gardens and Rueda's (2021) analysis of Barcelona's super-blocks demonstrate how participatory cultivation transforms residual infrastructure into civic commons. Within the Gulf, longitudinal work by Furlan and Shehada (2019) documents similar gains in public-realm sociality when small edible parks are introduced into Doha's suburbs. Although climatically distinct, these cases suggest that edible roundabouts could enliven neglected traffic nodes in Al Ain.

A third body of literature critiques desert cities' dependence on car-oriented infrastructure and explores micro-scale retrofits that can simultaneously improve thermal comfort and walkability. Extending Gulf-region walkability debates into the realm of food systems, Alawadi, Anabtawi, and Almohtadi (2025) analyze mapping data to reveal how informal food-growing practices activate Abu Dhabi's residual public spaces and strengthen neighborhood resilience. Their Local Environment study situates urban agriculture within a broader framework of everyday urbanism, emphasizing the need for distributed, community-managed landscapes rather than exclusively high-tech, centralized farms.

Across these bodies of work, enduring success hinges on governance arrangements attuned to local socio-ecological dynamics. Ostrom's (2009) design principles for common-pool resources, subsequently adapted for urban green-space governance in Stockholm (Barthel et al., 2015) and Singapore (Tan & Jim, 2022), highlight the importance of clear stakeholder roles, graduated sanctions, and nested governance. Synthesizing these insights, this study formulates a design-and-governance framework that is structured around four interlocking domains—spatial configuration, climate adaptation, community participation, and municipal integration. Each domain is operationalized through measurable indicators: (1) spatial configuration captures roundabout size, pedestrian catchment, and angular integration; (2) climate adaptation assesses shade potential, irrigation efficiency, and surface-temperature mitigation; (3) community participation gauges stewardship tenure, volunteer diversity, and knowledge-sharing practices; and (4) municipal integration examines funding models, policy alignment, and maintenance protocols. Together, these domains form a matrix that guides site selection, design decisions, and governance arrangements for edible roundabouts in hyper-arid, automobile-dependent contexts, as illustrated in Figure 1.

Figure 1: A Neighborhood Urban Farming design-and-governance framework synthesized from the literature review and spatial assessment.



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3. Methodology

3.1 Spatial Analysis and Study Site Selection

Al Ain, often called the “garden city” of the Emirates, provides a distinctive experimental platform because its internal neighborhood roundabouts are both plentiful and culturally familiar points of orientation. Based on spatial assessment of Al Ain’s district characteristics, three sample districts—Al Mu’tarid, Al Hili, and Al Yahar—were purposefully selected to capture the city’s broad spectrum of residential morphologies, densities and socio-economic profiles. Given the limited research on urban farming in the region, the selection criteria did not focus on the presence of non-edible or edible plants. Instead, the aim was to evaluate the broader concept of urban farming concept to explore residents’ willingness to engage in such activity. Al Mu’tarid, situated near the historic oasis, is characterized by compact block patterns, limited residual open space, and the highest pedestrian trip density within Al Ain’s municipal reporting zones. Al Hili, the mid-density case, is organized around super-block villas and community facilities, making it a representative microcosm of conventional suburban-style development in the Gulf. Al Yahar, located on the urban periphery, exhibits the lowest dwelling density but contains the largest supply of under-utilized municipal land, including numerous oversized secondary roundabouts. Taken together, the three neighborhoods allow the study to contrast micro-conversion opportunities across dense heritage fabric, mature middle-ring suburbs, and rapidly expanding edge developments. Therefore, the selected neighborhoods for this study represent three different morphologies to examine alternative patterns of residents’ participation and perception of urban farming.

3.2 Data Collection

Data gathering followed a sequential mixed-methods design that drew exclusively on the materials now available—namely GIS layers supplied by Al Ain Municipality, one neighborhood-wide Google Form questionnaire, five semi-structured interview transcripts, and systematic field notes collected on site. First, municipal base maps (1 : 1 000) and February 2025 Google Earth imagery were imported into ArcGIS Pro 3.2. A 400 m network buffer—approximately a five-minute walk—was drawn around every residential block in Al Mu'tarid, Al Hili, and Al Yahar. Twelve secondary roundabouts satisfied two selection criteria: (a) adjacency to housing, schools, or mosques and (b) absence of formal landscaping. For each node we documented radius, surface cover, remnant vegetation, and pedestrian-network angular-integration scores. Second, an Arabic–English questionnaire was disseminated via Google Forms between March and April 2025. After removing incomplete or duplicate entries, 107 valid responses remained. Items gauged perceived social, cultural, environmental, and economic benefits, walkability impacts, and potential stewardship barriers. Third, five community farmers participated in concise (10–20 minute), structured interviews held either in site or via encrypted video call during May 2025. Conversations probed design priorities, maintenance routines, and cultural meanings associated with neighborhood cultivation. Fourth, systematic field observation rounds were conducted monthly from late March to mid-July 2025 (three visits per roundabout per month: morning, afternoon, evening). Research diaries captured the "lived atmosphere" of each site—who lingered, who merely transited, children's play patterns, use of improvised shade, and subtle signs of emergent stewardship (watering cans, swept paths, hand-written crop labels). Together these four evidence streams supply an integrative socio-spatial dataset that underpins the multi-layered analyses reported in results section.

4. Results

This study generated insights from three interlocking empirical streams: survey responses from residents across Al Ain's neighborhoods, structured interviews with local community farmers, and spatial analysis of underutilized roundabouts. Together, these datasets construct a multi-dimensional picture of urban agriculture potential and community readiness in hyper-arid, car-oriented environments.

4.1 Quantitative and qualitative perceptions

This section triangulates quantitative evidence from a neighborhood survey (n = 107), qualitative insights from five semi-structured interviews, and geospatial analytics of secondary roundabouts to illuminate the multifaceted feasibility of community-managed urban farms in Al Ain. Table 1 summarizes the survey results, Almost three-quarters of respondents reside within Al Ain (73.8 %), and the sample skews young (43.9 % aged 18–25) and relatively well-educated (83.2 % holding at least a bachelor's degree). More than one-third are full-time students, reflecting the city's large tertiary-education community. Survey responses (n = 107) reflect strong conceptual support for urban agriculture as a vehicle for community enhancement. A notable 93% of participants agreed that edible gardens can strengthen social ties, and 88% viewed them as contributing to a stronger sense of neighborhood identity. However, just 46% reported participating in urban farming activities on a weekly basis—revealing a meaningful gap between expressed support and consistent engagement. Residents prioritized cultural and ecological values: 90% emphasized the importance of preserving local traditions through native planting palettes, while 71% ranked shade provision as essential, and 68% favored water-efficient irrigation solutions. In environmental terms, 65% linked edible landscaping with biodiversity enhancement. Economically, 93% identified the initiative as an avenue for either reducing household food costs or generating income, and over half (52%) preferred hybrid governance models that combine public and private support. These responses collectively illustrate the perceived multi-functionality of edible landscapes, yet they also suggest that enthusiasm alone may not translate into long-term stewardship without institutional and infrastructural scaffolding.

Table 1: Quantitative and qualitative perceptions results

Participants' Demographic							
Tool	Total	18–24	25–44	45–54	55+	Expats (n)	≥ Bachelor’s Degree (%)
Survey	107	47	41	14	0	46	83.2%
Interviews	5	2	2	0	1	0	90%

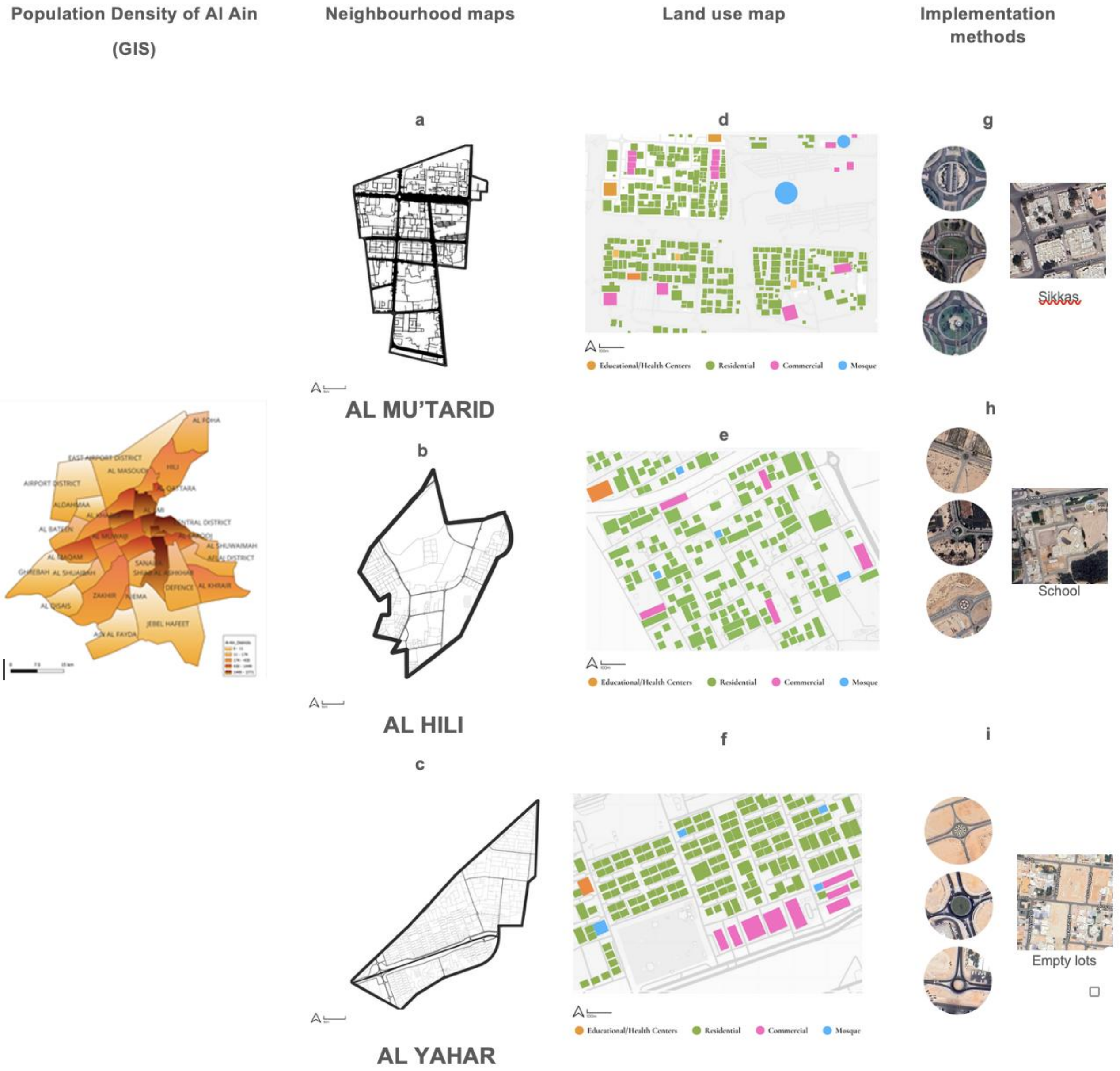
Survey Results	
Participate in urban farming weekly	46%
Agree: edible gardens enhance neighborhood identity	88%
Agree: edible gardens strengthen social ties	93%
Support native planting to preserve local traditions	90%
Prioritize shaded space in edible garden design	71%
Favor water-efficient irrigation systems	68%
Link edible landscaping with biodiversity enhancement	65%
Believe initiative can reduce food costs or generate income	93%
Prefer hybrid governance (public–private collaboration)	52%

The interviews revealed recurring cross-cutting themes that deepen and nuance the statistical findings. First, social learning and intergenerational exchange emerged as vital dynamics. Participants described the process of cultivating edible plants as a catalyst for neighborhood cohesion. One respondent reflected: “*It turned strangers into friends, just from watering the same basil bush*.” Another noted, “*We didn’t plan to teach, but the young ones watch and learn without asking*.” These exchanges positioned gardening as a quiet yet powerful mechanism for intergenerational transmission of both technical and cultural knowledge. Second, respondents consistently articulated design prerequisites that condition participation. Shaded seating, accessible water sources, tool storage, and lighting were framed not as preferences but as infrastructural necessities in Al Ain’s extreme climate. As one participant stressed, “*You cannot expect someone to stand in the sun for an hour just to plant mint. There has to be a bench, a tree, something.*” This sentiment underscores that even the most committed volunteers will disengage if the physical environment is hostile or poorly maintained. Third, operational challenges were widely acknowledged. Issues ranged from heat-induced crop failure to irregular volunteer attendance and plant damage from stray animals. One resident explained, “*Some days it’s just me and the sun. No one comes, and the plants wilt. It’s disheartening*.” These reflections echo the engagement gap seen in survey responses and highlight the need for adaptive maintenance strategies and more consistent community outreach. Finally, interviewees expressed a sense of civic authorship and symbolic attachment to the edible spaces they helped cultivate. Gardens were described as “small landmarks” that represent both hospitality and environmental stewardship. As one participant observed, “*When I see the thyme growing in the roundabout, I feel like it belongs to all of us, not just to the city*.” These statements reinforce the conceptual shift from beautification to co-ownership, positioning edible roundabouts as shared symbols of collective care

4.2 Spatial feasibility analytics

Spatial analysis confirmed that selected roundabouts possess the physical characteristics necessary for micro-scale agricultural transformation The comparative analysis of the three selected neighborhoods; Al Mu’tarid (high density: 1,449–3,771 people, located in the dark brown zone), Al Hili (Medium to high density, 430–1,449 people, situated in the orange to dark), and Al Yahar (Low density, 0–11 people, positioned in the light yellow zone) as shown in Figure 2

Figure 2: Spatial analysis results for each neighborhood. Font Authors



Twelve secondary roundabouts were identified within a 400-meter pedestrian catchment area of housing clusters, schools, and mosques—supporting the principle of proximity as a determinant of equitable spatial access. Based on the density characteristics of each neighborhood and the insights from the spatial analysis (Figure 2), different typologies should be applied accordingly (see table 2). Network analysis showed that Al Mu’tarid offers the highest angular integration, reflecting compact and walkable block morphology. Al Hili, while less dense, exhibited coherent pedestrian routes connecting roundabouts to civic amenities. In contrast, Al Yahar demonstrated low connectivity but offered the largest reserves of available land, indicating potential for scalable interventions in peripherally located neighborhoods. Field observations conducted between March and July 2025 further identified informal appropriation of roundabout spaces—such as impromptu gatherings and limited planting activity—despite clear barriers including poor shade coverage, lack of signage, and inconsistent irrigation. These findings validate both the latent potential and the infrastructural shortcomings of edible roundabouts as currently conceived. Taken together, the data substantiate three critical insights. First, community appetite for edible landscapes is high, and their perceived value extends beyond food production to include cultural identity, public health, and civic pride. Second, structural barriers—namely inadequate shade, irregular maintenance, and limited institutional support—undermine the translation of enthusiasm into sustained participation. Third, spatial conditions are variably conducive to conversion: while some roundabouts are optimally located and well-integrated, others require significant adaptation. These findings informed the development of a design-and-governance framework structured around four interdependent domains: spatial configuration, climate adaptation, community participation, and municipal integration. The framework not only distills the conditions for success but also provides a transferable structure for policy and practice in other arid-region cities seeking to reimagine their public infrastructure through the lens of edible urbanism.

Table 2: Summary of preferred typologies by neighborhood, categorized by density.

Neighborhood	Applicable typology	Reason
Al Mu'tarid	Sikkas & micro-roundabouts	High density, strong foot traffic, minimal voids
Al Hili	Full-scale roundabouts + educational adjacent Lots	Balanced density, strong connections
Al Yahar	Empty lots + roundabouts	Low density, spatially rich but socially weak

5. Discussion and conclusion

This study investigated how micro-conversions of neighborhood roundabouts into edible landscapes can advance walkability, social cohesion, and sustainability in hyper-arid, car-oriented environments. Framed by three research questions, it explored the relationship between neighborhood form, resident perception, and governance; assessed the social, spatial, and symbolic outcomes of roundabout conversion; and translated these insights into a transferable design-and-governance framework. Grounded in four interdependent domains—spatial configuration, land use, community participation, and municipal integration—the findings contribute to a deeper understanding of how urban agriculture can support social sustainability in Gulf-region cities.

In response to the first question—how spatial form, community perceptions, and governance shape feasibility—the study found strong alignment between network integration and resident support in areas like Al Mu'tarid and Al Hili. However, as with Galal Ahmed et al. (2024), who documented spatial fragmentation in Abu Dhabi housing clusters, the data here reveal that spatial proximity alone does not guarantee access or usability. Many roundabouts lacked walkable paths, signage, or clear visual cues—factors that shape the perceived legitimacy of public space. This complicates models such as CPUL (Viljoen et al., 2005), which emphasize spatial continuity but overlook infrastructural and cultural barriers to use. The data suggest that successful edible landscapes in Al Ain must be intentionally woven into neighborhood life—not simply located within range but made legible and inviting to diverse users.

Regarding the second question—whether edible roundabouts enhance walkability, social cohesion, and environmental performance—the findings were both promising and conditional. Survey responses and interviews strongly affirmed the social value of community gardens, echoing Ilieva et al. (2022) and Antunes et al. (2024) in their emphasis on bonding, place identity, and intergenerational learning. Participants described edible roundabouts as “small landmarks” that signal shared ownership and environmental care. Yet structural limitations—irregular attendance, lack of water, and inconsistent upkeep—tempered these benefits. This supports Ramadan et al. (2025), who found that even well-intentioned urban agriculture projects in the UAE falter without adaptive infrastructure and clear roles. This study demonstrates that social sustainability is not just a product of participation, but a function of supportive conditions: shade, seating, accessible pathways, and predictable stewardship mechanisms. When these are absent, enthusiasm alone cannot sustain engagement.

The third research question—how findings inform a transferable framework—was addressed through the synthesis of observed enablers and constraints. The revised framework centers land use as a pivotal domain, emphasizing the need to reclassify ornamental infrastructure as productive civic assets. This aligns with international case studies (e.g., Masdar City, 2024) that show how multi-functional land use increases urban resilience. Yet unlike high-tech vertical farms or energy-intensive rooftop greenhouses, the Green Circles model advocates for low-tech, socially embedded forms of productivity. Roundabouts, typically overlooked and underused, become civic micro-parks that serve food, climate, and culture simultaneously. The framework's domain of community participation is grounded in local practices, affirming that stewardship is built through repeated, relational action—not through policy mandates alone. Echoing Ostrom's (2009) governance principles and the UAE's Plant the Emirates campaign goals, the study illustrates that residents are willing co-creators of public space when they are recognized, resourced, and respected.

Municipal integration remains the most contested domain. While national policies call for widespread greening and sustainable urbanism (as seen in SDG 11), on-the-ground mechanisms for neighborhood inclusion remain weak. This study adds to Jung and Awad's (2023) critique of Gulf "sustainable cities" by demonstrating that policy ambition is insufficient without municipal coordination, funding pathways, and long-term planning support. The Green Circles model offers a grounded response: rather than bypass formal planning processes, it proposes a governance architecture that enables alignment between municipal departments, community groups, and site-level interventions. In doing so, it reframes underutilized traffic infrastructure as platforms for social sustainability—not just design opportunities, but democratic arenas for everyday participation, shared responsibility, and public identity-making.

Ultimately, this study contributes to regional and global scholarship by showing how micro-scale land use transformations can produce outsized social and spatial value. By replacing the ornamental with the edible, the decorative with the participatory, and the fenced with the shared, edible roundabouts shift the trajectory of public space in hyper-arid cities. The four-domain framework offers both diagnostic clarity and design guidance, and the empirical evidence affirms that socially sustainable cities are made not only through master plans or mega-projects, but also in overlooked circles of land—when reimagined with care, collaboration, and critical design.

Despite these contributions, the study has several limitations. The sample size for interviews was modest, reflecting five participants whose experiences, while rich, may not capture the full diversity of urban farming actors in Al Ain. Additionally, while the spatial analysis covered a representative set of roundabouts, it did not extend to longitudinal monitoring of post-conversion sites, limiting the ability to assess long-term performance or maintenance cycles. The absence of microclimatic data also constrains environmental generalizations, particularly regarding temperature regulation and biodiversity benefits. Finally, the framework has not yet been tested at policy level or scaled across different governance regimes, which limits its immediate generalizability.

While this study considered spatial proximity and walkability, accessibility remains limited in Al Ain's given the car-centric context and should be examined further. Future work should assess the long-term performance of edible roundabouts in terms of volunteer retention, ecological health, and governance. Comparative studies across other Gulf cities such as Sharjah, Muscat, or Riyadh could clarify how urban form and cultural context shape implementation. Longitudinal post-occupancy research evaluations, combined with environmental sensing, climate modeling, and participatory design would strengthen both spatial outcomes and social impact.

Acknowledgement

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PROBLEM-BASED COLLABORATIVE LEARNING ON SMART HOME DESIGN AND IMPLEMENTATION

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ABSTRACT

Problem-based collaborative learning is encouraged in tertiary education to facilitate students to be better prepared for encountering various challenges in professional settings. This paper is about the problem-based collaborative learning among undergraduate building design students, architectural engineering students, and electrical and electronic engineering students in 2024 with a particular focus on the design and implementation of smart home features within tiny houses. Both building design and architectural engineering students first designed tiny houses in groups and prepared physical models, which were then transitioned to electrical and electronic engineering students for the design, installation and testing of different smart home functionalities, including light control with motion sensors, energy harvesting, regulation of indoor temperature, as well as the display of environmental data. At the end of the unit, all 37 participating students were invited to complete an online student-experience survey to provide their feedback on the unit design and their learning experience. Their feedback was collected for analysis. Such problem-based collaborative learning aims to foster teamwork, facilitate communication, and highlight practical hand-on skills, which are essential in contemporary professional practices in built environment and engineering disciplines.

Keywords: Problem-based collaborative learning; Learning by doing; Industry ready; Teamwork; Smart-home functionalities

1. Introduction

Problem-based collaborative learning is integral to design studio units which require students to address issues at stake and propose creative solutions. Design studio units are regarded as laboratories for testing ideas with innovative outcomes (Bates, 2015). Students' problem-solving skills and critical thinking abilities are fostered by tackling the design task from different perspectives and unfolding an open-ended exploration for various possibilities (Salazar et al., 2020).

In this paper, an undergraduate design studio unit with problem-based collaborative learning in 2024 is examined as a case study for identifying favourable attributes that can promote active learning and enhance student engagement.

2. Methodology

In view of the richness of ideas generated in design studio units, the notion of 'design as research' has been accepted within the realm of research involving creative works. The intellectual rigour and reflective nature of creative processes have been considered important for academic inquiry (Armstrong, 2000).

In an undergraduate design studio unit delivered in Australia in 2024, both building design students and architectural engineering students were involved. They were required to address the housing crisis in Australia by proposing tiny house design. Facing challenging issues in terms of soaring house prices and rents, a surge in population growth, and increasing mortgage stress, tiny houses seem to provide an alternative housing option (Chau, 2023).

In the beginning of the unit, students were provided with a detailed unit guide listing learning outcomes, assessment tasks and requirements, assessment rubrics and relevant reference materials for them to have an overview of the unit and associated expectations within the broader research agenda. Students were required to work in teams with intensive peer discussion and exchange of ideas. The agreed client briefs and final physical models were subsequently used by electrical and electronic engineering students for designing, installing and testing multiple smart home functionalities that were compatible with tiny house design. Students involved were invited to participate in questionnaire survey to collect their feedback on such learning arrangement. The survey findings were useful in identifying favourable attributes for promoting active learning and enhancing student engagement.

3. RESULTS

For facilitating students to understand the overall context of tiny house development, a guest talk delivered by officers of Mount Alexander Shire Council was arranged to cover the current corresponding tiny house policies, which allow tiny house on wheels to park on properties with existing dwellings within the local government area of the Mount Alexander Shire followed by a question-and-answer session for students to engage with the invited guest speakers (Mount Alexander Shire Council, 2023) (**Figure 1**).

Figure 1: Guest talk by local council officers

Figure 2: Case study by students

Before developing own design, students studied available tiny house design on market and presented their findings in class for sharing among themselves (**Figure 2**). Students' case study covered overall design strategies, spatial arrangement, material selection, colour palette, architectural detailing and construction system. The purpose of the case study was not to encourage students to imitate existing design, but to arouse their learning motivation to familiarise with the current standard and identify any area of improvement.

Through the study and design inspiration of precedent cases, students were required to formulate own design objectives and express the initial design concepts of their own tiny house design. Some students drew sketches, diagrams, perspectives (**Figure 3**) and drawings (**Figure 4**) to illustrate their preliminary ideas. Individual presentation was arranged for students to present their work-in-progress and share initial concepts and knowledge. Students were encouraged to provide feedback to their classmates for peer learning.

Figure 3: Hand-drawn perspectives

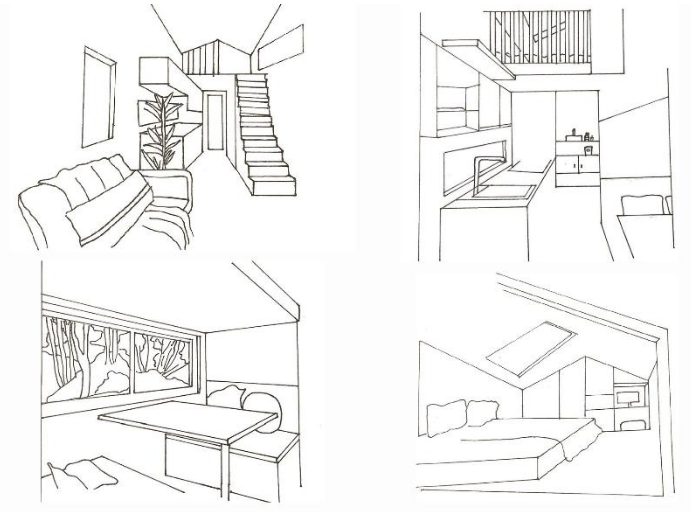
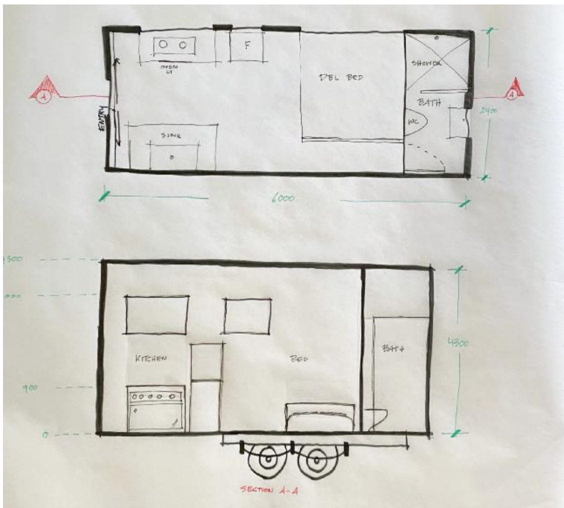


Figure 4: Initial design drawings



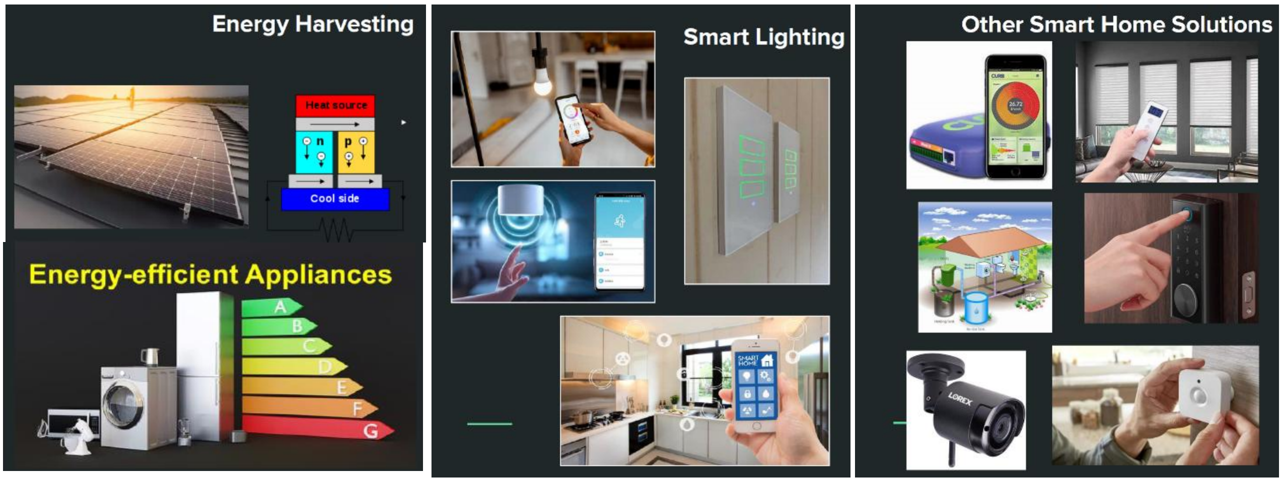
Two factory visits were arranged for students to gain their first-hand spatial experience of tiny houses and have better understanding of the production process involved (**Figures 5-7**). Factory visits provided valuable opportunities for students to engage with tiny house manufacturers, who provided guided tours for students, explained various material samples and elaborated relevant construction details. Such experiences were very helpful for students to design their own tiny houses and proceed detailed design development.

Figures 5-7: Factory visits for students to engage with tiny house manufacturers

Subsequent to individual presentations on case study and initial design, students worked in groups to consolidate conceptual design from each group member to formulate the group schematic design. Building design and architectural engineering students were encouraged to work together to form cross-disciplinary synergy within the same group. This enables students to learn how to communicate and collaborate with others, especially those from different disciplines. Each student played an important role to contribute own idea, knowledge and expertise in the group. The BuddyCheck online portal allowed students to evaluate the performance of their group members with confidential scores which contributed to the overall scores of students.

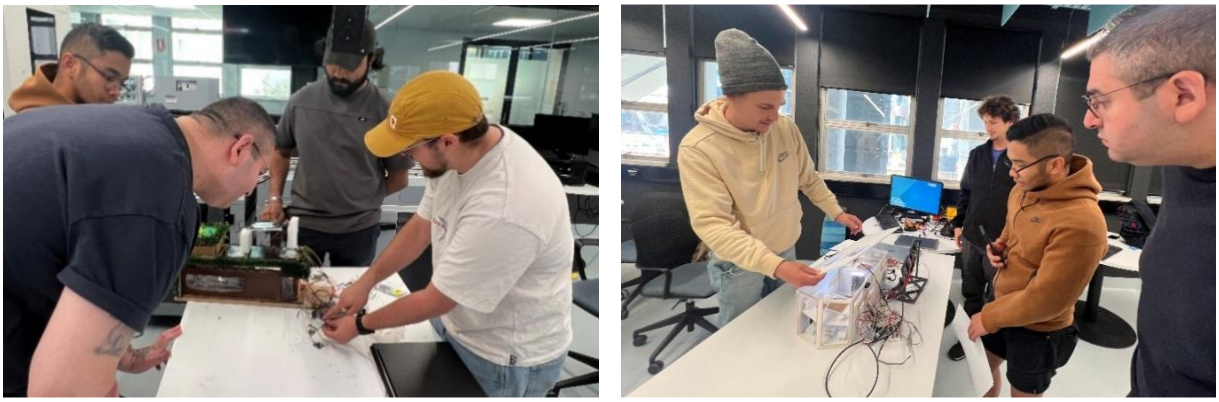
Each group was required to develop a client brief with specific client family profile, needs and requirements in terms of smart home functionalities (**Figures 8-10**). Various aspects of smart home functionalities include: energy harvesting via solar panels/ batteries, light control with motion sensors and dimmers, fan control with temperature/ humidity sensors. Based on the developed client briefs, students further proceed the schematic design, detailed design, leading to final design at the end of the unit.

Figures 8-10: Smart Home Functionalities



The client briefs with smart home functionality requirements and the physical tiny house models prepared by building design and architectural engineering students in the first semester were subsequently passed to electrical and electronic engineering students in another unit in the second semester for the design, installation and testing of different smart home functionalities. At the end of the year, a session was arranged for cross-disciplinary student engagement to see the outcomes and to exchange their respective learning experiences throughout the process (**Figures 11-12**).

Figures 11-12: Cross-disciplinary student engagement on smart home functionalities



At the end of the unit, all 37 participating students were invited to complete an anonymous online student-experience survey to provide their feedback on the unit design and their learning experience. Their feedback was collected for analysis, including:

- *The best parts of this unit are the tiny house visits and the practical areas.*
- *I appreciate the unique design challenge of a tiny house.*
- *The best aspects of this unit are probably the team discussion and team collaboration.*

4. Conclusion

Cross-disciplinary problem-based learning encourages students to examine interdisciplinary topics and enables them to learn how to engage and collaborate with others from different disciplines. Through this design studio unit on tiny house design, favourable attributes for promoting active learning and enhancing student engagement are: factory visits, involvement of industry partners, teamwork and group discussion, and a collaborative project to tackle real-life challenges. This paper is limited to a particular undergraduate design studio unit. Considering that cross-disciplinary collaboration is essential in industry design practices, similar engagement opportunities should be embedded in the overall curriculum design for students to be more industry-ready before graduation.

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THE ROMAN PUBLIC BATHS' THERMAL AMBIENCES

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ABSTRACT

The Roman bathing buildings are these monuments that most illustrate the social, cultural and even economic life of the Roman city. Furthermore, this worldwide Roman heritage constitute the study object of several investigations affiliated to several research fields even if the most numerous are carried out by the archeologists. However, the morphological, the functional and the structural aspects are the mainly studied ones and in function of the currently visible ruins. Since some decades, other aspects are investigated including the Romans' way of life within both urban and architectural spaces. This paper attempts to reveal the sensory dimension of the Roman way of life, with a particular focus on the thermal atmospheres of Roman public baths. Following the revelations drawn from the referential writings of the Roman architect Vitruvius, several architectural components and characteristics are extracted from the Roman baths related literature, highlighted by means of personal visits to some still visible ruins inside the archeological sites, and identified within both iconographic authentic sources and exhibition models. Thus, this research allowed to better understanding the following aspects: i) the principles of orientation of the Roman baths and its different spaces towards sun and wind; ii) its spaces, architectural components and constructive techniques playing a specific role in terms of thermal regulation; and iii) the sensory lifestyle inside this building.

Keywords: Roman baths; Thermal ambience; Iconographic sources; Textual sources.

1. Introduction

The sensory dimension played a central role in Antiquity. Statues were vividly painted, and literature relied heavily on rich sensory imagery to evoke emotional and perceptual experiences (Toner, 2014). This multisensoriality prevails also within the urban environment itself, where the ancient city was perceived not only by sight but also by all the human senses. Exploring this multisensory nature of the ancient spaces requires the analysis of sensory data extracted from various types of sources: (i) textual and linguistic, (ii) epigraphic and iconographic materials, and (iii) increasingly, modeling and digital reconstructions. Although these traces are often incomplete, they provide historians and researchers with a fundamental basis for interpretation. However, to approach a historical objective reconstruction, a critical and interdisciplinary analysis of these sources is essential (Clave, 2017). In the context of architectural heritage, in particular the case of the monumental historical buildings, several researchers have attempted to define and characterize their spatial ambiances. This has often required the development of conceptual models that decompose ambiance into tangible indicators. Among the notorious contributions in this way could be cited those of Joanne (2003), Bott (2008), Belakehal (2009), Salvione-Deschamps (2013), Mahroug (2017), and Ziani (2021). Belakehal (2024), in particular, suggested that ambiance emerges from the complex interplay between four key components: (i) the context of the urban space or the architectural space (climatic, social, and cultural), (ii) the spatial and formal characteristics of the architectural space itself, (iii) the physical signal (light, heat, sound, odor, etc.), and (iv) the user's perceptual and behavioral conducts in response to this signal. Referring to this conceptual model, this research work aims to explore the ambiances within the Ancient Roman Heritage buildings. Among the architectural spaces of Roman Antiquity, the public baths buildings stand out for their ability to regulate thermal environments but also to provide a rich multisensory living experience.

Throughout Roman civilization, public baths underwent remarkable development, achieving a high level of functional and organizational performance (Gatti, 2011). From simple hygienic spaces, they evolved into complex and multi-purpose facilities offering leisure, relaxation, and social interaction (Tardo, Floriano, Liuzzo, Gueli, Stella, Margani, 2025). As Garette (2001) points out, Roman baths were characterized by a sequential gradation of differently heated rooms. The main spatial components of a Roman public bath are: (i) Frigidarium (cold room for bathing), (ii) Tepidarium (warm room for relaxation), and (iii) Caldarium (hot room with heated water and steam). The transition from one temperature zone to the other was an essential part of the Roman bathing ritual, believed to afford health benefits and to promote well-being. This specific use of the bath's spaces, known as the "circuit" or "cursus" implies the users' moving through the various baths in a precise sequence, starting within the hotter rooms and ending inside the colder ones.

This study aims to enrich to this knowledge field by investigating how thermal ambiences were designed and experienced in Roman public baths. Drawing on various sources of information, this research aims to better understand the impact of architecture upon sensory experiences, particularly thermal ones, within the public bath complexes of the Roman world.

From a more contemporary perspective, the results of this research will primarily serve as on-site tourist information, allowing for a better understanding of the past sensory life within this specific type of building. They will also lay the foundations for a comparative analysis with the architecture of the Byzantine and Ottoman baths that succeeded them in Algeria. These results will thus constitute a reference for the design of contemporary baths, in continuity with their historical precedents. Moreover, this study aims to demonstrate how the thermal aspects of Roman baths (heating, cooling, hot water, etc.) could influence contemporary practices and inspire sustainable, climate-friendly approaches from both technical and economic perspectives. This paper not only reconstructs the sensory thermal ambiences of Roman baths but also discusses how these lessons can inspire sustainable design in contemporary architecture.

2. The Roman Public Baths: An overview

The Roman public baths were built in cold, temperate and hot regions of the Roman Empire (Figure 1.2.3).

Figure 01: Roman baths of Caracalla, Roma, Italy.

Figure 02: Roman hypocaust, Beirut, Lebanon.

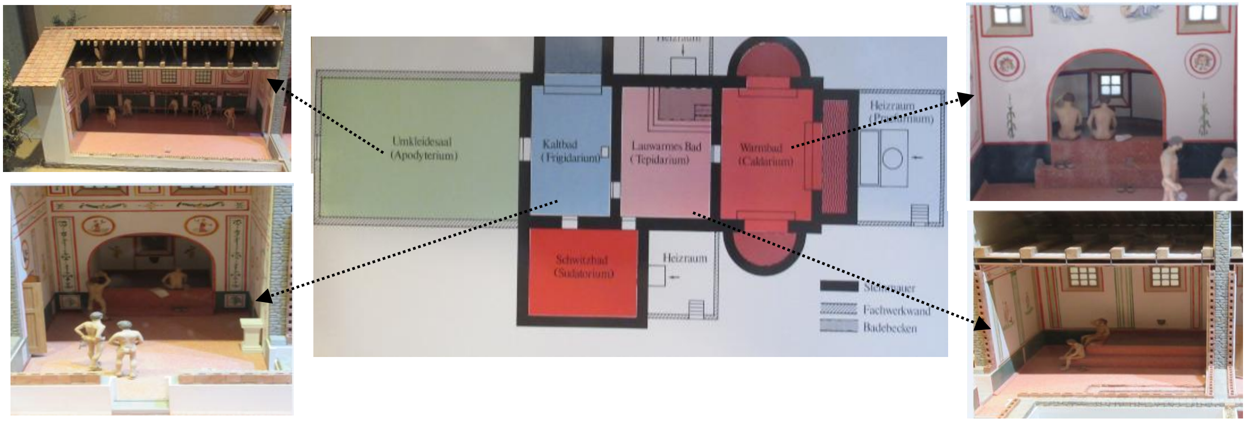
Figure 03: Roman baths of Antoninus, Carthage, Tunisia,

Font: Authors

In function of their locations, the Roman Public Baths could be categorized as follows: i) numbers, ii) size and disposition. This categorization or classification of the Roman Public baths corresponds to their location out of the city, in its peripheral areas and/or in its center (Thébert, 2013).

However, and despite this varied geographical and territorial locations, the main spatial components of a Roman public Bath are commonly: Frigidariumi), ii) Tepidarium, and iii) Caldarium (Figure 4). Inside each of these latter, and from one to another, the users should live a specific sensory experience including thermal, daylighting among ambience's signals (Hamilakis, 2014; Betts, 2017).

Figure 4: The sequential route through the various rooms of a Roman bath illustrated by means of a plan view and a sectional model of the Roman bath at the Saalburg fort, Germany.



3. Methodology

Due to their state of ruins, the sensory life within such Ancient built heritage can be explored mainly throughout historical sources including iconographic and Latin textual sources (Von Ehrenheim and Prusac-Lindhagen, 2020). This qualitative study lays the foundations for a future quantitative characterization using research techniques allowing the measurements of the thermal physical environment within a virtual restitution of these Roman baths ruins. Hence, the first methodological step consists of a literature review carefully focused on environmental aspects aiming to identify: i) the main recommended orientations, towards sun and wind, for the Public thermal baths, ii) spatial components, architectural devices and constructive technical details having a specific role in the building's thermal regulation, and iii) the use of the various spaces of this building. Then, this hierarchical analytical process is applied for other sources of information and collected data including in situ visits to Roman archeological sites as well as Museums' exhibitions. In the following, the thermal ambiance related data is presented dependently of the information source.

3.1 Vitruvius' recommendations for building the Roman Public Baths

Vitruvius' architectural treatise, namely "De architectura", is considered as one of the first architectural books, in history (1st century BC), presenting the principles of Roman architecture, often called "balneae" as "thermae" by him. In the tenth chapter of the tenth book of this architectural treatise, Vitruvius reserves implicitly an important part to the recommendations for of the thermal environment of Roman baths. He explained how baths should be designed in order to maintain a comfortable temperature inside. However, Vitruvius' information is limited to a specific phase in the genesis of the thermal baths. This should be due to the fact that at his era, the baths had not yet reached their peak as was the case with the imperial baths from the 2nd century AD.

Firstly, he points out that location and orientation were so closely linked. The building requires a site that is a very hot and not orientated towards the north. This explains why the unheated rooms (Apodyterium, Frigidarium) must be oriented towards the north whilst the heated rooms (caldarium, Laconicum and Sudatorium) have to face the south in order to take full advantage of the midday and afternoon sun. Therefore, moderately heated rooms (Tepidaria) will assume the role of a gradual thermal transition from cold to warm environments (Yegül, 2010).

Secondly, he allowed a great importance to the size of the baths that have to be proportional to the number of the city or district people. The review of Vitruvius' various recommendations turns out that more importance is given to the heated sector (hot and warm room) that was finely detailed oppositely to the Bath's cold sector shortly described. Moreover, he underlines the combined impact of the spatial characteristics and architectural devices on both thermal and luminous atmospheres of the hot room. According to him, the successive decreases of temperature levels inside the rooms (from the hot room, then to the warm one and finally to the cold room) as well as the windows' shape and size are considered to be the primary sources of generating the bath's various inner ambiences. The main purpose of such association of building parameters is to simultaneously avoid heat loss in hot rooms, and take advantage of sunlight. Unfortunately, sound, taste, tactile and olfactory ambiences are lucked within Vitruvius's description.

3.2 Thermal ambiences generated by architectural devices in Roman public baths

Several visits of Maghrebian, Middle-Eastern and European archeological sites and museums, provided the opportunity to observe in situ the ruins of the thermal regulation related spatial components and constructive details cited in the reviewed literature.

3.3 Heating system (hypocaust)

Roman baths remain archaeologically famous for their highly distinctive heating components. The earliest system of all caldarium heating elements was the hypocaust system. Therefore, Y. Thébert (2013), in his research, divided the history of the baths into two major periods namely baths' "before" and those "after" hypocaust. This system located under the bath’s current floor posses the double function of conserving the heat and avoids its loss by means of the isolation (Mowdy, 2016).

3.4 Large openings

The importance of the windows is not mainly related to their size that could be very wide in many caldaria. Hence, it is associated to their accessories allowing four possible use's scenarios: i) open, ii) glazed, iii) with shutters, or iv) glazed with shutters (Oetelaar, 2013). In Roman Public Bath buildings, the windows are generally tall with an arched top similarly to those observed in the great imperial baths in Rome and beyond (Ginouvès, 1992).

3.5 Double glazing

Since the 1st century AD, the Roman public thermal's openings were equipped with double-glazed closing systems in order to limit heat loss. In addition, this device performance was reinforced by external shutters. Moreover, this component was advantageous in terms of limitation of the condensation deposit on the windows. In this era, glass was therefore a decisive step in the improvement of heating techniques and allowed the development of ever larger and brighter thermal buildings (Figure 5.6) (Vipard, 2005).

Figure 05: Graphic reconstruction of the double-glazing system in wood and glass of the suburban baths of Herculaneum, Ercolano, Italy. (**Source**: Baatz, 1991).

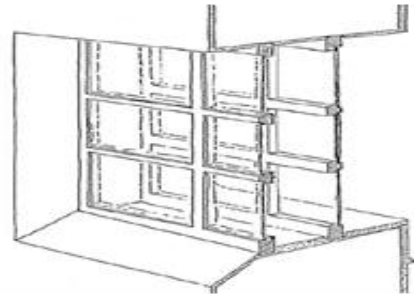


Figure 06: Apodyterium of the Stabian Baths,Pompeii,Italy.(**Source**: Foy, 2008).

3.6 Hollow brick walls

In Roman baths, hollow brick walls were extremely important for the caldarium's heating systems. These cavity walls allowed a temperature homogeneously distributed throughout the room. As air moved from one side of the wall to the other, the entire room was eventually heated. Finally, these cavity walls allowed air circulation in such a way that heated air could be channeled to other parts of the complex. This technique saved energy, which would be more efficient in heating each room (Mowdy, 2016). Additionally, they maintained a constant temperature in the lowest and highest spaces (Ring, 1996).

4. The Roman baths' Ambiences according to mosaics and painting

In the Bardo Museum in Carthage (Tunisia), the famous mosaic of Lord Julius, dating from the 3rd century AD. J.-C represents scenes of the daily life of a rich family (Figure 7).

This latter's house contains four round towers topped with cupolas that should be thermal baths. Among these cupolas, three ones are surmounted by chimneys from which smoke rises. According to Broise (2011), these three cupolas may roofing the hot rooms, while the largest one, devoid of smoke, could be a Frigidarum (Broise, 2011). This mosaic reveals (02) two important information related to the Roman baths. Firstly, it is the size of spatial components illustrated by the huge volume in relation to the other ones. Secondly, are the various built materials expressing their rich decoration and luxurious covering materials such as the marble. This latter covering material is not away from all the sensorial thermo-tactility within this kind of buildings.

On her side,R. Molhot (2011) considers that the mosaics were often used to decorate the floors of thermal baths. She reveals that among fifty-six known Roman mosaics representing labyrinth, fourteen ones come from baths. More precisely, this researcher undelines that seven of these latter were located inside North African baths (Figure 8) (Molhot, 2011). Distinctively, labyrinths were a popular theme for mosaics because of their entertaining roles in which bathers can decipher the labyrinth while they relax. As a floor decoration, the labyrinth can reinterpret the space it delimits, and going through these spaces contributes to mentally constructing the bather as a heroic athlete (Molhot, 2011).

Also, Roman mosaics acknowledge widely about that era's social practices. They concretely testify of the currently adopted practices within the Roman baths, such as sport activities, but did not illustrate any of those illustrating personal hygiene (Figure 9).

Figure 07: Mosaic of Lord Julius in Carthage currently kept in the Bardo Museum,Carthage, Tunisia (**Source**: Authors).

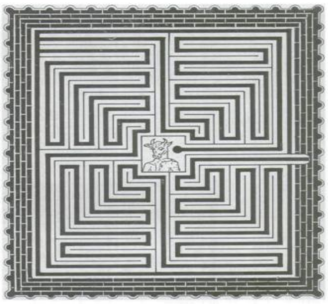


Figure 08: Labyrinth mosaic drawing, 150-200 CE, Frigidarium, Roman baths ,HippoRegius, Algeria, by E.Stawski, **(Source:** Molhot,2011).

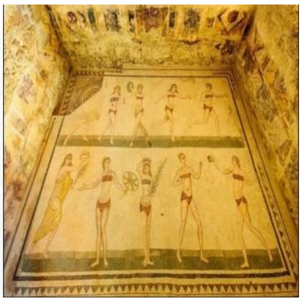


Figure 09 Sporting Activities in the Thermal Baths: The Mosaic from the Villa del Casale, Piazza Armerina (4th Century AD), Sicily,Italy. (**Source:** Authors).

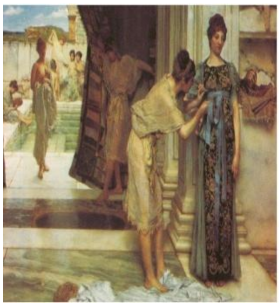


Figure 10: A scene of life within the Frigidarium in a Roman bath: A painting of Sir Lawrence Alma-Tadema dating from 1890 (**Source**: Frétard, 2014).

As an evolutionary art work, ancient painting illustrated the Roman baths as scenes of daily life, with figures bathing, relaxing and entertaining using with bright colors and simple shapes. Such content informs about the Roman baths spaces' authentic as well as imagined ambiences prevailing at a specific era of the Roman civilization. The difference between the Roman bath's inner thermal environments is clearly expressed by the 19th century artist Lawrence Alma-Tadema. The first plane of this painting presents a scene of clothed users in the Frigidarium whilst its background shows the Tepidaria with nude people (Figure 10).

5. The Roman Public Bath's ambiences: What Roman remains and Museums' exhibitions inform about?

At the present time, some Romans baths ruins are still functional and allow living some segments of the baths' thermal sensory experience in roman baths of Khenchela. Differently, the non-functional baths' spatial components as well as the constructive materials help largely for stimulating our imagination about these buildings and their inner ambiences (Figure 11).

Moreover, such imagination is increased by the means of models exhibited within site museums. The section model of the roman baths of SAALBURG fort in Germany shows clearly the use patterns of the various spatial components of the Roman bath (Figure12). Additionally, this model includes the bathers inside with varying clothing in respect to the different thermal areas. Hence, it shows clearly the significant role played by tactility in the thermal sensorial experience within the Roman Public baths.

Another significant example of everyday life in Roman baths is the virtual reconstruction of an indoor pool in the baths of Carnuntum, near Vienna (Austria). The bright interior, decorated with aquatic wall paintings and complemented by a fountain, offers valuable insights into the spatial organization and the ambience of Roman bath culture (Figure 13).

Figure 11: Current life within the Roman baths of Khenchela, Algeria. **(Source:** Authors).

Figure 12: Authentic old life inside the Roman baths illustrated by a 3D physical model, SAALBURG fort, Germany. **(Source**: Authors).

Figure 13: Authentic old life inside the Roman baths illustrated by a 3D virtual model Carnuntum, Austria. **(Source**: Authors).

6. Conclusion

The Roman public baths architecture has been approached from the sensorial living experience and mainly the thermal one. The data collected, examined and analyzed demonstrates a great mastery of the Roman civilization's developments in terms of thermal regulation strategies. Encompassing a set of orientation based principles, spatial organizations, constructive materials and users' behavioral conducts, these strategies achieved a minimization of the heat loss and provides good thermal comfort for users. Moreover, this research work highlighted that such achievements surpassed users' comfort needs to provide to them a rich, varied, and dynamic sensory experience strongly linked to the inner physical thermal environment in all various climatic territories. In sum, there is no doubt that the Roman public baths constituted a reference for the succeeding civilizations builders even if the inner ambiences knew some changes. In other words, thanks to the sophisticated technical system, the Roman public baths have a direct influence on many subsequent typologies such as Byzantine and Ottoman ones. They still provide valuable lessons for contemporary architects due to providing valuable insights into the synergy between functionality, sustainability, and social experience in contemporary architectural practices.

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WALKABILITY ASSESSMENT OF THE UNITED ARAB EMIRATES UNIVERSITY CAMPUS

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ABSTRACT

Universities are increasingly described as "small cities" due to their size, population, and diversity, positioning campuses as urban microcosms that mirror the dynamics of larger urban environments. Aligning campus spatial quality with sustainable city standards can enhance environmental performance, student well-being, and overall livability. However, ensuring safe and comfortable walking remains a key challenge in hot-climate regions, where extreme heat undermines mobility and quality of life. This study applies the 5D framework of urban form to assess the micro-scale walkability of the United Arab Emirates University (UAEU) campus, addressing a gap in research on how limited walking culture and climatic stressors affect mobility in the Gulf region. A mixed-method approach will be employed, combining field observations, benchmarking against local sustainability guidelines (Abu Dhabi Street Manual and Estidama), and a student survey to capture both physical and perceptual dimensions of walking. The findings aim to inform evidence-based strategies for green campus design, including shaded pedestrian networks, energy-efficient mobility alternatives, and socially vibrant pathways. By framing walkability as a sustainability challenge, the study contributes to advancing climate resilience, reducing carbon dependency, and creating healthier, youth-centered campus environments

Keywords: Walkability, Campus design, Sustainability, Microclimate, and Green infrastructure.

1. Introduction

For the sake of future generations, campuses must evolve as sustainable, livable environments that benefit both individuals and society. Achieving this requires collective commitment, where the well-being of each student contributes to the success of the wider community. Within this context, creating a walkable campus is not a minor aim; it will have a direct positive impact on environmental sustainability, community vitality, and the physical and mental health of students (Alnehayan, 2024; Homoud & Jarrar, 2024).

This study investigates the existing walkability of the United Arab Emirates University (UAEU) campus, positioning it as a critical factor in advancing sustainability and green innovation. Through combining spatial mapping, personal journals, and student surveys, this research was able to capture both objective and subjective experiences of the campus environment. Evidence was drawn from relevant case studies and prior research (Alawadi et al., 2022; American Planning Association, 2022) to contextualize findings and identify best practices.

The analysis is guided by established frameworks, including the 5D and 7c models of urban form and walkability (Raymer, 2023; Riahi & Althani, 2024), as well as local sustainability standards such as Abu Dhabi Street Design Manual (ADSM) and the Estidama Pearl Rating System (UAE Government, 2024). Despite global research on walkability, limited studies have examined its dynamics in hot, car-centric regions like the UAE, where thermal comfort and cultural walking habits strongly affect mobility (Environment Agency – Abu Dhabi, 2025) This study addresses that gap by assessing UAEU's walkability through both physical and perceptual dimensions, ultimately highlighting opportunities to align campus design with sustainability goals and to ensure healthier, more resilient spaces for future generations.

2. Literature Review

2.1 Walkability in Arid Climates

The walkability of a place is contingent upon factors such as its connectivity, safety, and comfort. In arid regions, thermal comfort is more important. Alnehayan (2024) asserts that "excessive heat and dryness... render walking a less appealing... option" for urban residents, indicating that incorporating vegetation and water can markedly enhance comfort and encourage walking (Alnehayan, 2024). Homoud and Jarrar (2024) assert that Riyadh's extreme summer temperatures, reaching 50°C, and the absence of shade "deter walking and limit the utility of outdoor spaces." (Homoud & Jarrar, 2024). The lack of shade, benches, and water features causes an issue as it "discourages pedestrians from walking." (Homoud & Jarrar, 2024). Research in the UAE reveals a significant correlation between outdoor thermal comfort and walkability: the integration of vegetation and water features in Al-Ain markedly enhanced the Universal Thermal Comfort Index (UTCI). It was associated with increased pedestrian activity (Alnehayan, 2024). Qualitative studies in Abu Dhabi revealed that although climate did not statistically affect walking habits, "weather was the primary source of discomfort" for pedestrians (Homoud & Jarrar, 2024). Individuals in the Gulf primarily walk out of necessity, as the heat is the primary source of discomfort. The results show that walkability metrics like Walk Score and pedestrian mode share will stay low without any action.

2.2 Principles of Climate-Adaptive Design

Climate-responsive design is necessary to alleviate heat. Key strategies include enhancing shade, improving evapotranspiration, and selecting the right materials. Trees, pergolas, arcades, and other plants can all provide shade. To make hot cities more comfortable, it is best to have tree canopies that cover 30% to 40% of sidewalks (Homoud & Jarrar, 2024). Microclimate simulations (the ENVI-met study) show that adding both plants and water to a landscape lowers the UTCI the most. Water bodies like fountains and ponds help cool the air by evaporating. Orientation is essential; aligning streets with the prevailing wind direction and limiting east-west exposures helps reduce direct sunlight gain. The APA's Urban Heat Resilience Handbook states that "green and blue infrastructure, light-colored roofs and pavements, green roofs, and an expanded urban tree canopy" are essential ways to address heat in cities (American Planning Association [APA], 2022). These practices have been tested in experiments: a WRI evaluation shows that adding trees and using high-albedo surfaces can lower peak temperatures in cities (American Planning Association [APA], 2022). Climate-responsive retrofits on campus, such as sunshades over paths, drought-resistant vegetation, and more porous surfaces for airflow, have augmented pedestrian comfort and campus aesthetics.

2.3 Intelligent Urban Design for Thermal Resilience

When implemented on a larger scale, urban planning can integrate these methods into the system. Phoenix has started a big campaign called "Heat-Ready." It aims to build 100 "Cool Corridors" by 2030, each featuring approximately 200 trees, dedicated pedestrian and transit lanes, and designated areas for shade and water. Phoenix requires that new sidewalks built in the city center provide at least 75% shade (from trees or other structures) within five years of being put in (Raymer, 2023). Riyadh, Saudi Arabia, also initiated the Greenwave program, which encompasses the Green Riyadh Project. This initiative aims to increase green cover from 1.5% to 9%, plant 7.5 million trees, and lower summer surface temperatures by 2°C (Riahi & Althani, 2024). The "Sports Boulevard" project in Riyadh will create 135 kilometers of parkland corridors, connecting neighborhoods and public transportation with green spaces and walking paths that are always open (Riahi & Althani, 2024). These projects show how smart networks of shade and plants can help cities that are getting hotter. According to design theory, linear green corridors improve city ventilation by directing breezes and moving shade in areas where people walk (American Planning Association [APA], 2022).

The UAE policy also stresses the need to adapt to climate change. The UAE's Net-Zero 2050 strategy and National Climate Adaptation Program stress the importance of strong infrastructure, like green roofs, urban shading, and public cooling facilities (UAE Government, 2024). The Adaptation Plan for Abu Dhabi (2025–2050) clearly calls for "better shade provision, greening of thoroughfares, and urban afforestation" in city planning (Environment Agency – Abu Dhabi, 2025) which follows the global trend: C40 promotes the development of interconnected shaded pathways and parks to encourage people to move around in (American Planning Association [APA], 2022). The research indicates that most people believe design and planning changes can help in walking in hot weather, particularly in dry urban areas.

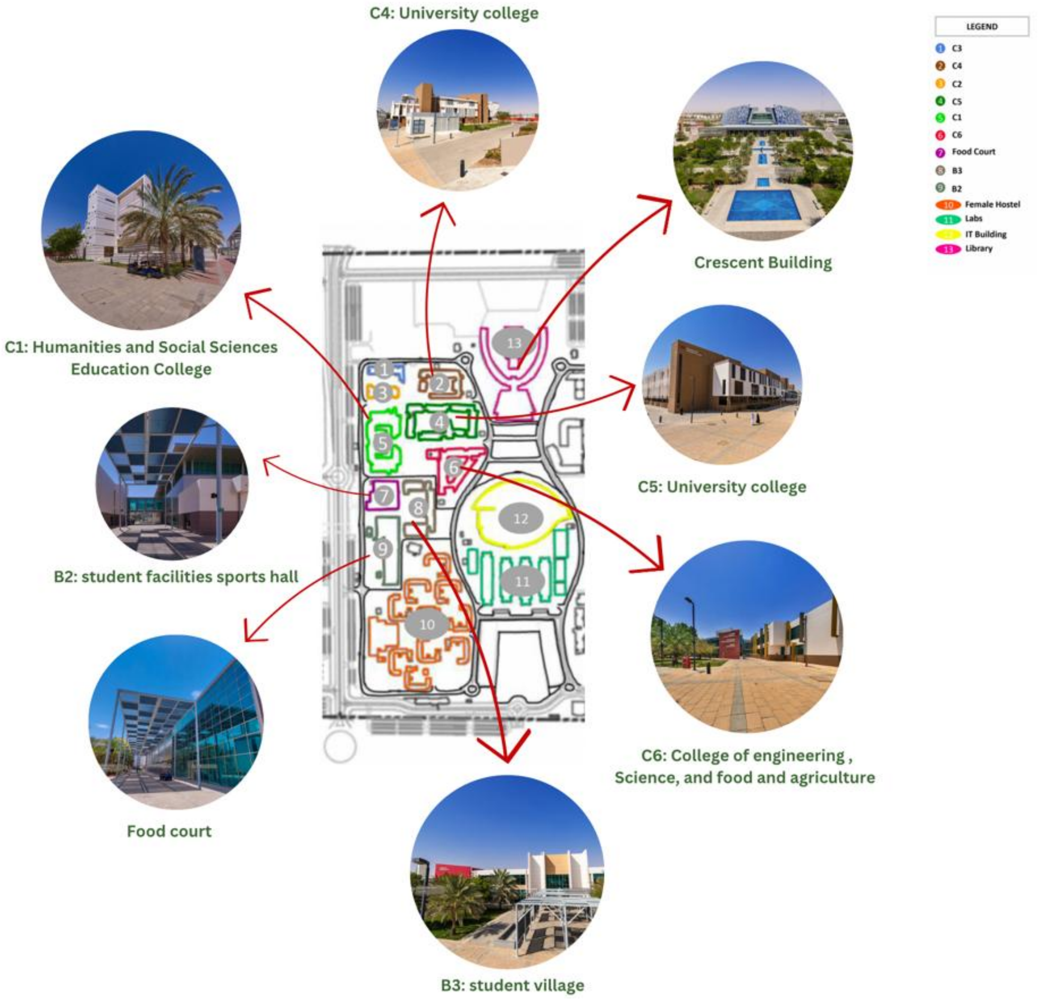
3. Methodology

The study utilized a mixed-methods assessment of UAEU campus walkability, combining spatial network analysis, a user survey, and benchmarking against best practices.

3.1 Spatial Syntax Analysis

At first, we used DepthMapX to create a model of the campus's pedestrian network using axial-line space syntax. We used campus GIS maps to draw axial lines along all the main pathways, plazas, and corridors. DepthMapX determined the integration and connection metrics for each segment, revealing its importance within the network (higher integration indicates better access and increased opportunities for through-movement). The method helped in distinguishing between main axis lines and secondary routes. We compared these numbers to the campus plan (Figure 1). Visibility graph analysis is used to look at how well people can see through essential nodes. Before being imported into DepthMapX, all geographic data processing was done in AutoCAD and ArcGIS. Standardized connectivity ratings based on campus size made it easier to compare them.

Figure 5: UAEU Spatial analysis, Female Campus. (Authors,2025)



3.2 Survey design

Alongside the spatial analysis, a structured survey was carried out to capture how students and staff actually experience walking around the UAEU campus. The questionnaire divided into four parts: (1) Demographics (age, academic affiliation, and patterns of mobility), (2) Travel Habits (how often people walk on campus and what modes of transportation they use), (3) Environmental Perceptions (Likert-scale evaluations of comfort related to shade, temperature, signs, lighting, etc.), and (4) Suggestions (open-ended responses about possible improvements). Our target sample size was around 300 responses to ensure reliable results. To reach this number, we distributed the survey link by email and posted QR codes in high-traffic areas. One key question asked, "I feel at ease moving between my classes during peak midday hours, how much do you agree?" Respondents were also asked what factors made walking uncomfortable, such as heat, glare, lack of lighting, uneven pavements, or insufficient seating. Responses were analyzed using simple descriptive statistics and were cross-tabulated by faculty to identify any notable differences in perception across disciplines.

3.3 Benchmarking criteria

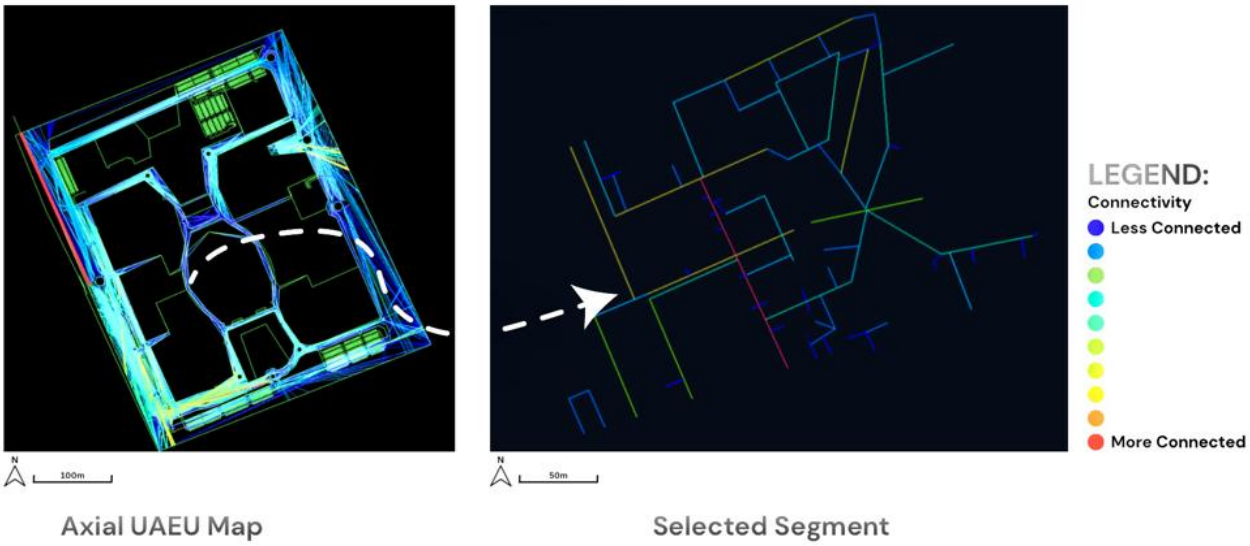
To put the survey findings in context, the campus was also evaluated against recognized standards of walkability and environmental design. For shade, studies recommend that at least 30% of sidewalks should be covered during the day in hot climates (Homoud & Jarrar, 2024; American Planning Association [APA], 2022; Raymer, 2023), while tree-to-population ratios and corridor greening are highlighted in global urban forestry strategies (Riahi & Althani, 2024; Environment Agency – Abu Dhabi, 2025). Connectivity was assessed with space syntax analysis, where higher angular integration values are associated with stronger pedestrian flows (Alawadi et al., 2022). For amenities, international campus plans typically recommend 25–50% canopy cover and a bench every 100 meters; by comparison, UAEU averaged about one bench per 200 meters (American Planning Association [APA], 2022; Raymer, 2023). Our benchmark table distilled these standards into measurable targets: for example,"≥30% of pathways under solid cover" (Homoud & Jarrar, 2024; American Planning Association [APA], 2022) and "mean integration ≥0.5 for primary routes" (Alawadi et al., 2022). These benchmarks allowed us to judge whether the campus was meeting, or falling short of, best practice (Alnehayan, 2024; UAE Government, 2024; Environment Agency – Abu Dhabi, 2025). Finally, survey "hotspots," where clusters of complaints were recorded, were overlaid on the spatial maps. This confirmed patterns of discomfort and pointed to priority areas for redesign. Together, the surveys, spatial analysis, and benchmarks provided both qualitative insight and quantitative rigor in evaluating the state of walkability at UAEU.

4. Results

4.1 Spatial Network Findings

The space-syntax analysis revealed clear corridors of pedestrian priority. High-integration axes run north-south through the main library and student center, and east-west along the central plaza (Figure 2). This match observed walking flows, with significant academic buildings aligning with these axes.

Figure 2: DepthMapX Female Section Segment.



Axial UAEU Map

Selected Segment

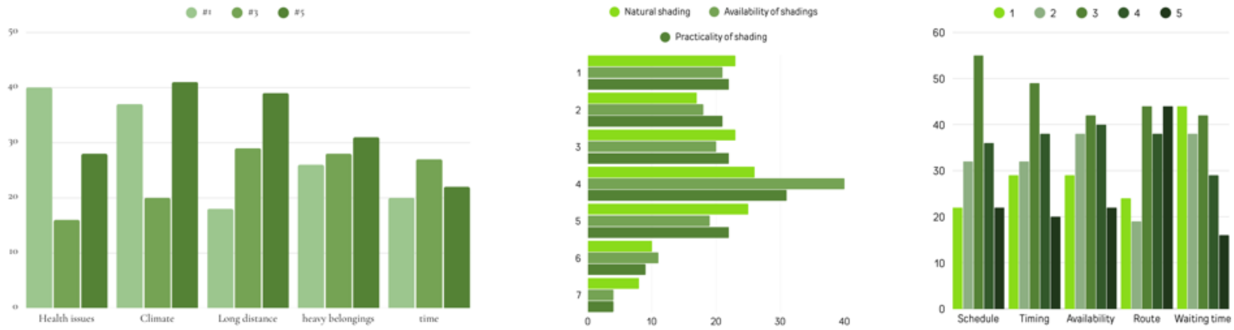
However, several peripheral routes showed low integration (<0.2 on normalized scale), indicating isolation and low footfall. Many of these low-score paths lack shade trees or coverings. Crucially, areas with high integration also experience significant user concentrations, but even there, heat stress is pronounced. For example, the central corridor had integration ~0.75 (max=1), yet the midday census showed empty pathways due to the scorching sun. Spatially, we identified "cold spots" of connectivity mostly in newer extensions of the campus, suggesting incomplete network links.

Overall, the campus's spatial graph has a moderate integration radius (global connectivity) but uneven distribution. The top 20% of paths (by integration) account for ~60% of pedestrian movement, implying a skew. This suggests one strategy: enhance the lower-integration paths by adding connective links or shortcuts (to distribute pedestrian load) and increasing natural surveillance along them (planting trees for shade). Integration maps also highlighted some potential bottlenecks – e.g., a narrow bridge near the Science labs had low visibility and formed a break in connectivity.

4.2 Spatial Network Findings

The poll, which had more than 250 answers from people in different faculties, showed that temperature is the primary concern. When asked, "What factors make you least likely to walk on campus?" 87% cited high heat/sun exposure as the primary concern (Figure 3). The second most significant issue was the lack of shade (65%), followed by insufficient water fountains (40%) and safety concerns after dark (22%). Only a small number (<10%) said that distance was a problem, which suggests that comfort, not architecture, is the main issue. Over 70% of students reported waiting for shuttle buses in the summer instead of walking short distances.

Figure 3: Survey walkability results on campus.



a. Obstacles that influence walkability habits. b. Shading rating 1-7 c. Bus rating 1-5

These results align with Alawadi et al.'s research conducted in Abu Dhabi, which revealed that health and comfort, rather than weather, were the primary incentives for walking; however, it also noted that "weather was the principal source of discomfort" for pedestrians (Alawadi et al., 2022). Qualitative comments from students (e.g., "the middle corridor resembles an oven at noon") supported these findings.

Ninety-two percent of respondents believed that adding trees or shade along the paths would encourage walking, and eighty percent thought that adding water misting stations or fountains would have the same effect. These results support Alnehayan's suggestions, which showed that adding plants and water features to Al Ain made it much more comfortable to be outside and walk around (Alnehayan, 2024). A cross-tabulation by faculty revealed that students shared the same attitudes; however, Science students, who often spent time outside near labs, were slightly more sensitive to heat.

The perceived walkability index, based on comfort and safety ratings, was low, with an average of about 2.1 on a 5-point scale (1 = very uncomfortable, 5 = fully comfortable). This score is much lower than the average of about 3.5 found in U.S. university surveys (American Planning Association [APA], 2022; Raymer, 2023) because there are no regional benchmarks for campus walkability.

4.3 Benchmarking Assessment

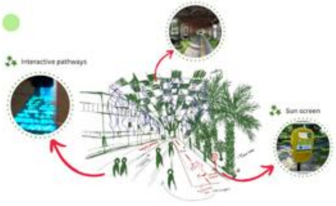
Using our criteria, UAEU's walkability composite score was below the target. For shade coverage, measurements showed that only ~15% of primary pathways are covered (through overhangs or trees), which is half of the 30% minimum standard commonly cited for hot climates (Homoud & Jarrar, 2024; American Planning Association [APA], 2022). Benchmarking against Phoenix's policy, which requires 75% sidewalk shade within five years of tree planting, highlights a significant shortfall 9 (Raymer, 2023). Connectivity (average angular integration from space syntax analysis) was moderate. Using a synthetic "Walk Score" method (based on destinations within a 10-minute walk), UAEU scored ~45/100, placing it in the "car-oriented" category according to Abu Dhabi walkability research (Alawadi et al., 2022). Amenities were also limited. The number of benches per person and water stations fell below peer campus norms. For example, American planning guidelines and APA heat resilience standards suggest a bench or resting stop every 100 m (American Planning Association [APA], 2022), whereas UAEU provides approximately 1 per 200 m. These benchmarks confirm the issues identified above: insufficient shade, amenities, and network balance.

5. Discussion

5.1 Shade and Vegetation

The most urgent step is simply to add more trees and shade along busy paths. Borrowing from Phoenix's "Cool Corridors," the campus could turn its main pedestrian routes (like those that link the library, student center, and lecture halls) into shaded walkways (Table 1) (Raymer, 2023). Planting hardy native species such as Desert Acacia or Mesquite close together would quickly boost canopy cover. Students themselves suggested tree-lined paths and lightweight tensile canopies for areas with the harshest sun. Their opinions align with our survey, where 92% of respondents said more trees would encourage them to walk. Shade does more than block sunlight: it cools the air and reduces radiant heat. Phoenix's Tree Equity program, which ensures shade in underserved neighborhoods, offers a model that UAEU could adapt for dormitory areas and commuter drop-off zones (Raymer, 2023).

Table 1: Sketches Developed based on the survey outcomes. Font Authors.

 **Dorm to College connection**	 **Library**	
 **Student's Village**	 Between colleges	**Key map**

5.2 Blue Infrastructure

Cooling features were also a common request in student feedback. Small fountains or misting stations at rest areas could drop local temperatures by a few degrees through evaporation. The American Planning Association describes such elements as "blue infrastructure" (American Planning Association [APA], 2022). In a dry climate like the UAE, efficiency matters, so these systems would need to rely on recycled or recirculating water.

Materials and Surfaces. Walkway materials can also make a difference. Light-colored or permeable paving can keep surfaces 5–10 °C cooler than asphalt, and Phoenix's "Cool Pavement" trials showed nighttime reductions of 8–13 °C with reflective coatings (Raymer, 2023). UAEU could explore similar materials, such as terrazzo or reflective sealants, and building façades that face pedestrian corridors could incorporate shading devices (brise-soleil or vertical fins) to cut glare and reflected heat.

5.3 Spatial Network Adjustments

Connectivity is just as important as shade. Our spatial analysis revealed a few low-use routes that could be redesigned to pass through green spaces. For example, a quiet path near the Engineering building could be rebuilt as a shaded garden shortcut. This kind of intervention mirrors Riyadh's Sports Boulevard, which blends walking and cycling routes with continuous greenery, and aligns with the city's wider Greenwave plan for connected park corridors (Riahi & Althani, 2024).

5.4 Policy Alignment

Policy Alignment. These design directions fit within the UAE's own sustainability agenda. The Net Zero 2050 Strategy stresses climate-responsive design and sustainable mobility (UAE Government, 2024), while Abu Dhabi's Adaptation Plan (2025–2050) calls for shade expansion, corridor greening, and new urban forests (Environment Agency – Abu Dhabi, 2025). UAEU could even adopt Phoenix's practice of appointing a "heat coordinator" (Raymer, 2023) and set concrete targets, such as boosting canopy cover by 30% or lowering midday path temperatures by 15 °C.

5.5 Cultural Inclusivity

Finally, design must respond to cultural realities. Homoud and Jarrar point out that walkability in Riyadh is shaped by gender norms and the prestige of car ownership (Homoud & Jarrar, 2024). UAEU is more diverse, but inclusion is still vital. Spaces should include seating with different levels of privacy, reliable lighting for safety, and wide, family-friendly pathways. Involving students directly through workshops, as piloted by our survey, will ensure that improvements match the needs and expectations of the campus community.

6. Final considerations

This research improves an early draft of a campus walkability plan into a complete analysis that focuses on sustainability and climate resilience at UAEU. We highlighted that even if the campus is physically connected, people can't move around freely because it's so hot. The primary findings are:

1. The primary difficulty with walking is the heat, which builds upon past studies in Al Ain that indicate how pleasant it is outside may change how individuals walk (Alnehayan, 2024).
2. Strategic corridors employ space well, but they don't give adequate shade, which makes them less valuable.

3. More than 90% of students are in favor of planting trees and building shade. They also strongly support green, shaded spaces.

We developed valuable suggestions, including planting numerous trees (cool corridors), erecting shaded structures, adding water features, and employing reflective materials, by merging spatial grammar, user feedback, and benchmarking. These designs follow the finest practices from throughout the world, such as the Greenwave project in Riyadh and the Cool Corridors initiative in Phoenix (Riahi & Althani, 2024). They also follow the UAE's climate policies, such as the Abu Dhabi Climate Change Adaptation Plan and the Net Zero 2050 Strategy. Implementing these ideas would make it easier to walk across campus, reduce heat stress, and improve long-term mobility.

In the future, initiatives may involve using heat sensors to monitor microclimates after an intervention and adding workers and visitors to the survey. In conclusion, environmentally friendly campus architecture that adapts to climate change promotes health and comfort while displaying UAEU's dedication to innovation and the UAE's aspirations for sustainability and users' well-being.

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