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Biophilic Micro-Modular Architecture as a Resilient Framework for Emergency Response and Temporary Healthcare

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Abstract

Temporary healthcare facilities routinely treat environmental quality as secondary to deployment speed and clinical capacity, leaving biophilic, emergency-healthcare, and modular-construction research disconnected. This study evaluates three deployed precedents, UNHCR/IKEA Better Shelter, Shigeru Ban's Paper Partition System, and the CURA pod, selected via purposive sampling for distinct construction logics with sufficient technical documentation. A nine-criterion Performance Evaluation Matrix was developed from published standards and top-tier peer-reviewed journals (five architectural and four environmental criteria) and used to evaluate the case studies. Each precedent was scored using an ordinal scale (low, moderate, or high). Daylight and Glare were simulated in Climate Studio, under the tropical climate of Dhaka, where point-in-time illuminance, spatial daylight autonomy (sDA), and spatial disturbing glare (sDG) were evaluated. All the precedents scored poorly on all of the nine criteria, with deficits concentrated in environmental comfort, natural ventilation, and biophilic integration. Simulations further reveal that high daylight availability does not ensure visual comfort, as unshaded designs suffer severe glare. Building on these evaluation findings, the study conceptually develops the Biophilic Micro-Modular Healthcare Unit framework: three spatial tiers governed by five design principles embedding environmental quality at the fabrication stage. The findings support extending emergency healthcare standards to include environmental and psychological performance criteria.

Keywords: Biophilic Architecture, Micro-Modular Design, Emergency Healthcare, Salutogenic Architecture, Temporary Facilities.

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1. Introduction

1.1 Background and Context

Permanent healthcare infrastructure has critical weaknesses during disasters. The 2010 Haiti earthquake damaged or destroyed more than 50% of hospitals and displaced more than a million people, leaving temporary shelters or clinics to function as the primary healthcare system (DesRoches et al., 2011). From the 2023 Turkey–Syria earthquakes, at least 15 hospitals suffered from partial or total damage in Turkey, forcing evacuation from at-risk facilities and transfer to on-field and modular

healthcare structures (Mohammad et al., 2023). The COVID-19 pandemic produced the same infrastructural collapse without a physical trigger. The modular hospitals built in response demonstrated that clinical capacity can be manufactured at speed (Chen et al., 2021). In each case, the emergency response was not only a temporary measure; it became the primary healthcare system.
Disaster situations raise concerns. One month after the February 2023 earthquakes, more than half of surveyed Syrian adults screened positive for probable PTSD, depression, or anxiety symptoms, the highest rates in severely damaged areas (Safiah et al., 2024; Soqia et al., 2024). Dhaka sits on soft alluvial deposits that amplify ground motion and are prone to liquefaction (Khan, 2016), while its densely built old city compounds this hazard, where non-engineered and unreinforced masonry buildings dominate and are mapped as highly vulnerable to seismic damage (Rahman et al., 2015). While assessments of primary healthcare facilities identify limited safety status and vulnerability in capacity during disaster situations (Murshid et al., 2019).
Such facilities stay longer than their design life predicts, so their spatial and environmental quality becomes a determinant of clinical outcome. Salutogenic theory shows that architecture contributes to health by strengthening comprehensibility, manageability and meaningfulness, rather than merely avoiding harm (Golembiewski, 2022). A systematic review of biophilic design in healthcare settings associates nature-integrated environments with reduced hospitalisation time, lower pain levels for patients, and reduced stress among care providers (Al Khatib et al., 2024). Also, a systematic clinical-environment review identifies a structured parameter set that associates specific biophilic features with therapeutic outcomes (Tekin et al., 2023).

1.2 Problem Statement

Three mature bodies of literature address parts of this problem and remain mutually silent. Biophilic and salutogenic research explains why environmental quality affects health but is addressed within permanent healthcare buildings (Al Khatib et al., 2024; Golembiewski, 2022). Research on emergency healthcare focuses on rapid deployment and clinical capacity (Kaim et al., 2026), with little attention to environmental quality (Brunoro & Mensi, 2024). Meanwhile, modular construction studies emphasize speed, cost, and transportability, treating environmental quality as a secondary consideration (Abbasi et al., 2024). Existing examples, such as the Better Shelter, Shigeru Ban's paper partition systems, and the CURA container, demonstrate that some of these ideas can be combined, but no approach integrates all three.
Three key gaps remain. First, an integration deficit: there is no framework that combines clinical, logistical, and environmental or biophilic performance. Second, an evaluation deficit: there is no common method to evaluate these aspects together. Third, a delivery-stage deficit: environmental quality is usually added after deployment, making it less likely to be included due to time and resource constraints.

1.3 Research Aim & Objectives

The aim is to develop a conceptual and performative framework for biophilic micro-modular healthcare architecture that supports emergency healthcare and logistical efficiency while also promoting psychological well-being in high-stress emergency contexts, such as disaster-affected urban environments. Three objectives, each derived from a question, structure the study:

1. Which architectural and environmental criteria determine whether a temporary healthcare unit can support clinical function and psychological well-being simultaneously? — To derive a nine-criterion performance evaluation matrix (PEM) from biophilic and Salutogenic design in healthcare, emergency-response, and modular architecture evidence.
2. Do the deficits of deployed precedents fall randomly across those criteria, or concentrate in particular ones? — To apply the PEM to Better Shelter, the Paper Partition System, and CURA, supported by daylight and glare simulation calibrated to Dhaka conditions.
3. How can biophilic strategies be embedded within micro-modular delivery so that environmental quality is achieved without extending deployment time? — To develop the

Biophilic Micro-Modular Healthcare Unit (BMMHU) framework: five design principles operationalised through three spatial tiers.

1.4 Significance and Structure of the Paper

This study makes three main contributions. First, it combines clinical, logistical, and environmental performance into a single evaluation framework, whereas previous studies assessed these aspects separately. Second, it introduces the BMMHU framework, which organizes biophilic design into three components: the clinical core, the biophilic envelope, and the urban interface. This helps determine when each design feature should be incorporated during the manufacturing and deployment process, ensuring that environmental quality is planned from the beginning rather than added later on-site. Third, the study recommends that Emergency Medical Team (EMT) standards should assess not only deployment speed and bed capacity but also environmental performance, recognizing psychological well-being as an essential criterion alongside infection control.

The paper is organised as follows. Section 2 reviews the three contributing literatures, constructs the conceptual model, and derives the evaluation matrix. Section 3 sets out the research design. Section 4 introduces the case studies, and Section 5 evaluates them through comparative and simulation-based analysis. Section 6 presents the BMMHU framework. Sections 7 and 8 discuss implications and conclude.

2. Literature Review & Theoretical Framework

This review addresses three literatures: biophilic and salutogenic design in healthcare, emergency healthcare architecture, and modular construction, which establish the basis for the theoretical framework of a Biophilic Micro-Modular Healthcare Architecture in Section 2.4. Then section 2.5 derives the performance evaluation matrix used in the case studies to assess the architectural and environmental suitability of emergency healthcare.

2.1 Biophilic and Salutogenic Design in Healthcare Environments

Two complementary theories underpin the design of health-supportive healthcare environments: biophilic theory, which explains what people need from a space, and salutogenic theory, which explains why such spaces support health. The biophilic design movement is grounded in Wilson’s (1984) biophilia hypothesis, which proposes that humans evolved with a deep connection to nature and possess an innate psychological need for natural environments. Kellert, (2018) organises biophilic design into three experiences: direct experience of nature (e.g., sensory contact with plants, light, air and water); indirect experience of nature (e.g., the use of natural materials, colours, patterns, shapes, forms, biomimicry and evocations of nature); and the experience of space and place (e.g., spatial configurations such as prospect-refuge and organized complexity).

Salutogenic theory shifts the focus of healthcare design from simply reducing stress and disease to promote health and well-being. People cope better with stress when their environment feels comprehensible, manageable, and meaningful, known as the Sense of Coherence (Golembiewski, 2022). However, there is still limited research on how these concepts can be translated into specific architectural design strategies (Rakhshani & Khakzand, 2025).

Systematic review associates biophilic hospital environments with reduced hospital stay, pain, anxiety, and staff stress (Al Khatib et al., 2024). Also, a systemic clinical-environment review identifies a structured parameter set which associates specific biophilic features to therapeutic outcomes (Tekin et al., 2023). The mechanism is not confined to planting; natural forms and patterns can also improve users' emotional well-being and sense of place (Al-azzawi et al., 2024), which matters where live planting is impractical.

Beyond visual and material contact with nature, a healing environment depends on thermal comfort, air quality, lighting etc. A systematic review of shelter design and displaced-population health identified problems such as poor indoor air quality, thermal discomfort and overcrowding impacting their health (Conzatti et al., 2022). Poor daylight and the absence of natural views have been associated with slower patient recovery (Joarder & Price, 2013). A comprehensive review by (Ulrich et al., 2008) found that elements such as daylight, views of nature, good acoustics, and clear spatial organization reduce recovery time, infections, medication use, and staff burnout.

2.2 Emergency Response & Healthcare Architecture

Research on emergency healthcare facilities, field hospitals and modular healthcare units, has primarily focused on rapid deployment, operational effectiveness and clinical capacity (Kaim et al., 2026; Petanidis et al., 2025), while environmental quality has received comparatively less attention (Brunoro & Mensi, 2024). Indoor environmental quality is well established as a determinant of patient recovery, stress and staff effectiveness, yet most existing evidence is based on permanent hospital settings (Ackley et al., 2024). Few studies evaluating occupant experience in temporary modular healthcare buildings are limited to single sites and subjective assessment (Muraj et al., 2023).

Emergency healthcare facilities are often designed for short-term operation, while recent studies suggest that temporary field facilities remain in service beyond their intended design life (Cerrahoğlu & Maden, 2024), and their post-emergency adaptation and reuse receive little research attention (Ma & Chen, 2025). This indicates that the assumption of short-duration use in emergency planning does not always hold in actual practice.

Emergency healthcare requires infection control between patients, spaces and staff areas. Experts recommend that improved cross-ventilation above 2 air changes per hour (ACH) can significantly reduce the risk of airborne infections (Morawska et al., 2020). WHO (2021) recommends natural ventilation efficacy, a minimum ventilation rate of 60 L/s per patient in general wards, while ASHRAE Standard provides guidance for ventilation in non-hospital temporary healthcare spaces.

CIBSE (2015) recommends a minimum daylight factor (DF) of 2% for general hospital rooms and 300–500 lux for examination and treatment areas. ASHRAE 55 (2020), which defines a comfort zone that varies with clothing and season rather than a single fixed range, yielding operative temperatures of approximately 20–23.5°C in winter and 22.5–26°C in summer. A relative humidity of 40–60%, widely applied in healthcare for infection control and occupant comfort (CIBSE, 2015)

2.3 Modular and Micro-Modular Construction Systems

Modularity is defined by the design and manufacture of standardized, self-contained units that can be fabricated off-site, transported, assembled and reconfigured on-site. Modular systems are primarily classified into three typologies: volumetric (self-supporting, three-dimensional modules); panelised structural panels assembled on-site into volumetric configurations); and hybrid systems combining both approaches (Lawson et al., 2014). Contemporary modular constructions confirm substantial reductions in delivery time and waste, and identifies digital fabrication and building information modelling as the mechanisms of that gain (Abbasi et al., 2024). In post-disaster application, a parallel logic supports transformable and reconfigurable units capable of adapting to changing spatial needs over an extended occupancy (Cerrahoğlu & Maden, 2024).

Spatial adaptability is a key feature of resilient emergency architecture. Flexible layouts, modular and movable partitions allow spaces to be reconfigured for different functions. These approaches are demonstrated in the WHO Emergency Medical Team standards and in examples such as the CURA pods and Rambam Hospital's convertible underground facility during crises (Capolongo et al., 2020; WHO, 2020). In healthcare, modular systems enable rapid deployment through field hospitals, prefabricated units and containers. Modular healthcare facilities are designed for rapid assembly and disassembly. According to WHO (2021), Type 1, Type 2, and Type 3 EMTs should be operational within 24, 24–36, and 36–48 hours after arrival, respectively, with all facilities fully functioning within 72 hours of a disaster. FEMA (2021) suggests that emergency facilities be integrated into existing urban systems by deploying them on existing hard surfaces without permanent foundations with provision of community accessibility and emergency routes. This approach enables rapid deployment within urban areas without major changes to the site or surrounding.

2.4 Theoretical Framework

Looking at the three areas of research together, one clear idea stands out: emergency healthcare buildings need to be quick to set up and medically efficient and they also must support people's physical and mental well-being. Biophilic and salutogenic design in healthcare explains why contact with nature is important for health. Studies on emergency healthcare show what happens when these qualities are missing. Modular construction, on the other hand, offers a practical way to combine speed, efficiency and environmentally sound design.

Together, these studies form the foundation for the Biophilic Micro-Modular Healthcare Architecture framework, highlighting the need for rapidly deployable modular systems that maintain spatial quality while integrating biophilic strategies, a promising yet underexplored approach (Figure 1).

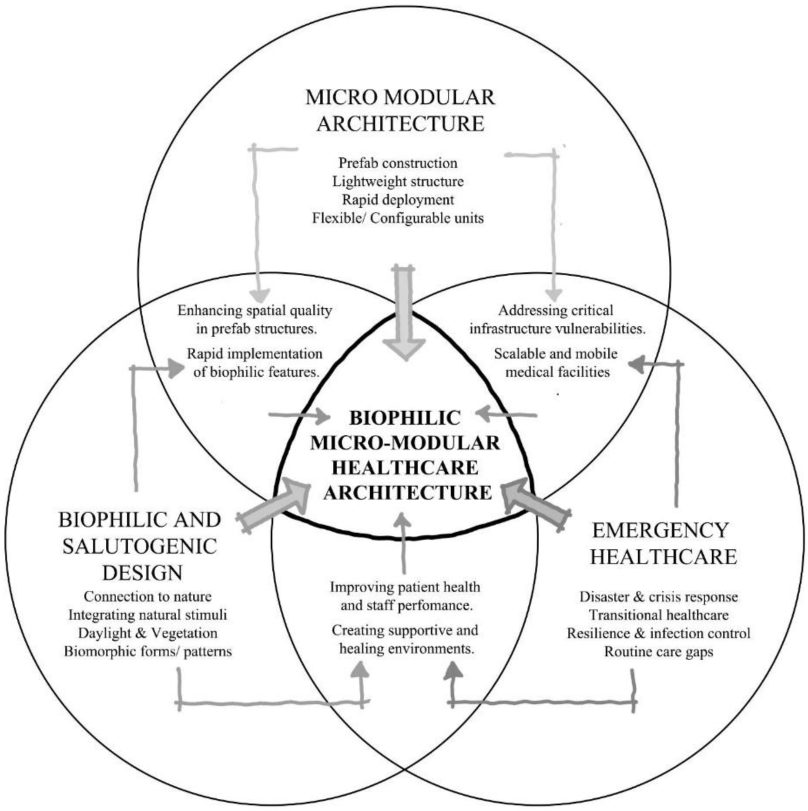

Figure 1. Tripartite theoretical framework underpinning Biophilic Micro-Modular Healthcare Architecture. (Source: Author, 2026)

2.5 The Performance Evaluation Matrix

2.5.1 Parameter selection: The nine criteria

Nine evaluation criteria were selected based on four requirements. Each criterion had to: (i) be supported by published standards or peer-reviewed research rather than the authors' judgment; (ii) be measurable for all three case studies using published data or simulation results to ensure fair comparison; (iii) avoid overlapping with other criteria; and (iv) contribute to clinical and logistical performance or occupant well-being.

Five architectural criteria (A1-A5) address the structural, logistical and spatial integrity of the unit; four environmental criteria (E1-E4) address passive performance, biophilic and salutogenic design integration. Definitions, thresholds and sources are consolidated in Table 1.

Table 1: The nine-criterion Performance Evaluation Matrix (PEM).

	Criterion	Operational definition	Threshold anchoring rating	References
A1	**Spatial adaptability**	Capacity to serve different clinical functions without structural alteration.	• Number of WHO EMT-compliant layouts possible. • Ability to spatial reconfiguration on-site	WHO (2021); Capolongo et al. (2020); Cerrahoğlu & Maden (2024); Lawson et al. (2014)
A2	**Rapid assembly and disassembly**	Elapsed time from arrival on site to clinical readiness, including services	• Total setup time • Benchmarked against WHO EMT operational targets: Type 1 ≤ 24 h, Type 2 24–36 h, Type 3 36–48 h; all facilities fully functional within 72 h	WHO (2021); FEMA (2021); Cerrahoğlu & Maden (2024); Ma & Chen (2025)
A3	**Infection control**	Capacity to prevent transmission between patients, spaces and staff zones	• Compliance with required ACH levels. • Use of HEPA filtration. • Clear separation of clean and dirty circulation.	ASHRAE 170 (2021); WHO (2021) Morawska et al. (2020)
A4	**Environmental comfort**	Thermal, luminous and acoustic quality, and connection to nature	• Temperature and ventilation strategy • Daylight and lighting quality • Presence of natural or biophilic features	CIBSE Guide A (2015); ASHRAE 55 (2020). Joarder (2013).
A5	**Urban system integration**	Ease of siting within existing fabric without ground works or utility alteration	• Deployment onto existing hard surface; • Ease of connecting to utilities (i.g. within 24 h)	FEMA (2021). WHO (2021)
E1	**Thermal comfort**	Attainment of comfort by passive means, mechanical backup as exception	• thermal comfort standards at 20–23.5°C in winter and 22.5–26°C in summer, 40–60% RH;	ASHRAE 55 (2020); CIBSE (2015).
E2	**Daylighting adequacy**	Provision of useful daylight with effective glare control	• Daylight factor ≥ 2%; 300–500 lux at examination and treatment surfaces with glare control.	CIBSE (2015); Joarder (2013).

E3	**Natural ventilation efficacy**	Achievable air change by passive means, appropriate to climate	• Minimum ventilation rate achieved by cross-ventilation. • Adequacy assessed against WHO natural-ventilation guidance.	WHO (2021); ASHRAE 55 (2020) Morawska et al. (2020)
E4	**Integration of biophilic elements**	Range of biophilic parameters instantiated across the three experiences	• Presence of biophilic and salutogenic design parameters. • coverage across three biophilic experiences (direct, indirect, and space and place)	Kellert (2018); Tekin et al. (2023); Al Khatib et al., (2024) Al-azzawi et al. (2024) Golembiewski, (2022) Joarder (2013).

2.5.2 Rating protocol

Each case is evaluated for every criterion against a three-level scale: low, moderate, high, based on the anchors shown in Table 2. This rating system follows two important principles. First, the ratings are criterion-based rather than comparison-based. A high rating means that a case meets the predefined criteria from literature review in Table 1, not that it performs better than the other cases. As a result, all three cases can receive a low rating for the same criterion if none of them meets the required standard. (Scielzo et al., 2023).

Second, an ordinal (low–moderate–high) scale is used instead of a weighted numerical scoring system. The three case studies provide different amounts of technical information, and the evaluation criteria are derived from different sources, including published standards and simulations conducted in this study. A weighted score would require assigning weights to clinical and psychological outcomes, but no accepted guideline exists for doing so. Since arbitrary weights can create a false sense of accuracy (Greco et al., 2019), an ordinal scale keeps the results clear and honest.

Rating follows a documented procedure: Each case is rated independently by two authors using the criteria in Table 2. If the ratings differ, the original source is reviewed together to reach a final decision. This rating process has some limitations. Since only three cases and two reviewers are included, the agreement indicates consistency but does not establish statistical reliability. The evaluation matrix is used to identify strengths and weaknesses across different criteria, rather than to measure the size of differences between the cases.

Table 2: Anchor descriptors for the ordinal rating scale.

Level	Anchor
Low	The threshold in Table 2 is not met, and the design contains no provision directed at the criterion
Moderate	The threshold is partially met, met only under favorable conditions, or provision exists but is not integral to the system
High	The threshold is met as an integral property of the system, independently of site conditions

3. Methodology

The study employs a qualitative exploratory methodology to examine the possibilities of employing biophilic design concepts for enhancing environmental performance and user experience of the temporary healthcare shelters. The research study is based on an interpretive research methodology, whereby the knowledge is generated through the synthesis of literature, case studies, environmental performance, and design development (Groat & Wang, 2013). The study was conducted in four major phases, which included (1) Literature Review, (2) Case Study Analysis, (3) Performance Analysis, and (4) Conceptual Framework Development, as presented in Figure 2.

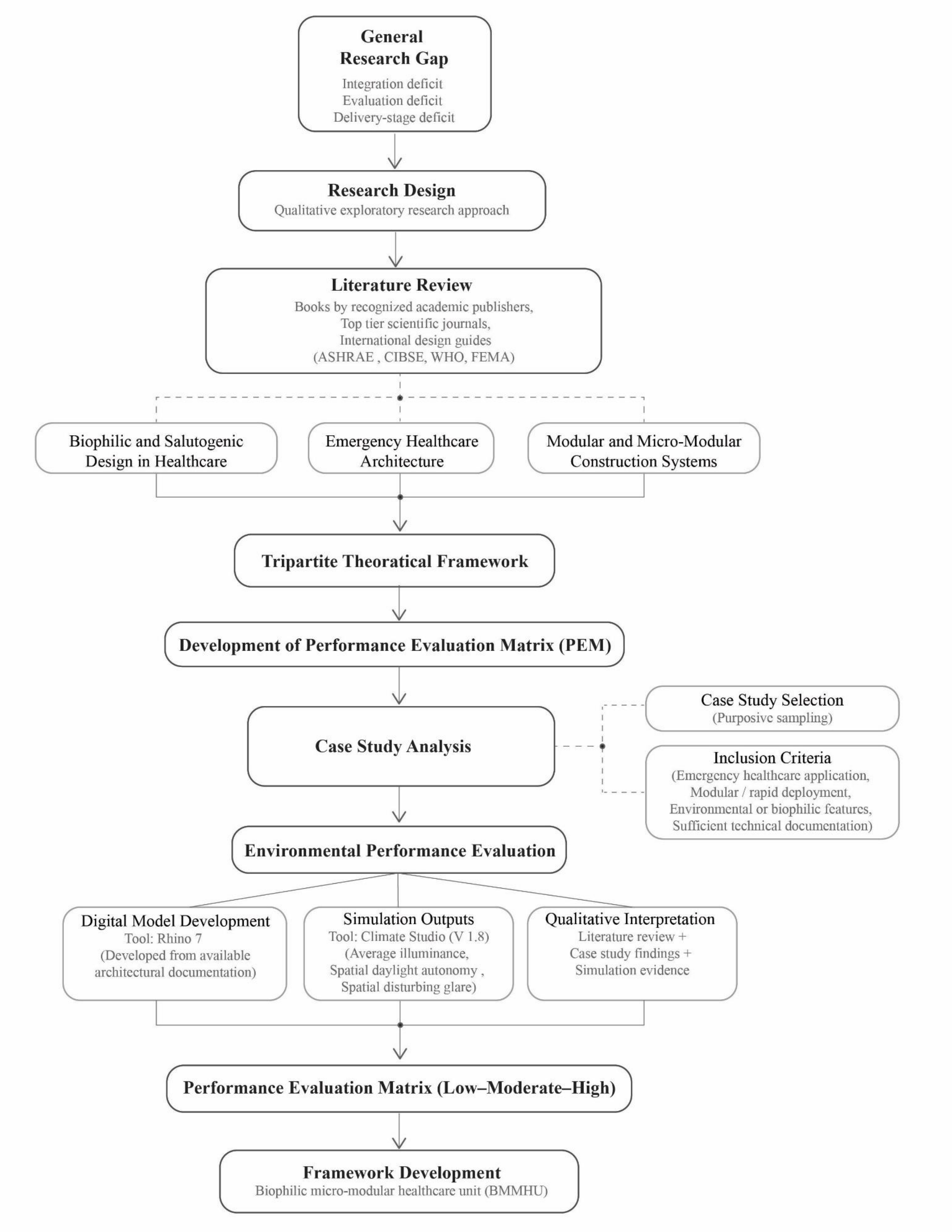

***Figure* 2**. *Structure of research methodology.* (Source: Author, 2026)

3.1 Literature study and Performance Evaluation Matrix development

The first stage was a systematic literature review, which provided the theoretical background for the study. The literature study was based entirely on desktop-based secondary data. It involved aspects such as modular healthcare architecture, emergency healthcare facilities, biophilic design, and environmental performance. The sources included books by recognized academic publishers, scientific journals, international design guides, and policies on the aspects mentioned above. Recent peer-reviewed Scopus or Web of Science-indexed journal articles were given highest priority. International standards and technical guidelines such as ASHRAE Standards, CIBSE Guides, FEMA, WHO Guidelines, etc were particularly important for architecture and environmental simulation.

The results obtained from the literature review assisted in identifying the research gaps and developing a nine criterion Performance Evaluation Matrix (PEM), which formed the basis of analysis of the case studies. The rating protocol was developed based on the literature review and each case was assessed with a criterion-based three-level scale (low, moderate, high) by two independent reviewers with consensus achieved through source verification

3.2 Case Study Selection and Analysis

Three international case studies—Better Shelter, Paper Partition System (PPS-4), and CURA—were chosen by means of purposive sampling according to preselected criteria. The three case studies have been chosen because each of them represents a different way of designing temporary healthcare architecture such as prefabricated shelters. Projects that lack enough architectural documentation and projects whose primary purpose is to provide shelter during an emergency rather than healthcare services were not included in the study. The two modular healthcare solutions Better Shelter and CURA have been selected since these solutions were designed for use in diverse geographical and climatic conditions rather than for a specific location. This makes them suitable for assessing their context-specific environmental performance and adaptability to the climatic and geographical environment of Dhaka. On the other hand, the Paper Partition System (PPS) has been selected as it has already been implemented in Japan which has similar climatic features to those of Bangladesh like warmth and humidity and the country is also vulnerable to natural disasters. All of the projects were selected because: (i) they were designed specifically for use in emergencies or temporary situations in the field of health; (ii) utilized modular or fast-deployable building systems; and (iii) had sufficient published technical data about their designs and performance for comparative purposes.

3.3 Performance Evaluation

For supporting the qualitative analysis, digital models of the three case studies were built using Rhino and analysed using Climate Studio (Version 1.8). Climate studio is a simulation software which employs the Radiance and Daysim simulation engines for daylight performance analysis. Environmental performance simulations were conducted in Climate Studio (Version 1.8) using the BGD_DH_Dhaka-Shahjalal.Intl.AP.419220_TMYx.2004–2018 EnergyPlus Weather (EPW) file. The weather file represents the climatic conditions recorded at Hazrat Shahjalal International Airport, Dhaka, Bangladesh (Latitude: 23.84° N, Longitude: 90.40° E; WMO Station ID: 419220) and is based on a Typical Meteorological Year (TMYx) developed from hourly meteorological observations collected between 2004 and 2018.

Although Better Shelter, CURA, and the Paper Partition System (PPS) were originally designed for different geographical contexts, the objective of this study was to assess their performance under the climatic conditions of Dhaka. Thus, using the same weather file for all simulations enabled a fair comparison of their thermal comfort, daylight availability, and natural ventilation performance, while also evaluating their suitability and adaptability for application in Dhaka.

The standard material and glazing properties were assigned according to published data and the comparable construction material. The surrounding buildings and trees were not considered as the boundary conditions were maintained the same in all the cases. The simulations were meant to provide environmental evidence and hence no field calibration or validation was carried out due to lack of access to the case studies selected from abroad.

The environmental simulations evaluated indicators such as daylight availability, average illuminance, Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE). While these data were not statistically analyzed, they were considered in terms of qualitative interpretation in order to aid in the comparative analysis of the environmental performance of each shelter. This information helped in validating the results of the literature survey and architectural study in relation to daylight quality.

3.4 Development of the Conceptual Framework

Finally, the findings from the literature review, comparative case studies, and performance evaluation were analysed to create the conceptual framework for the Biophilic Micro-Modular Healthcare Unit (BMMHU). A thematic synthesis approach was used to identify recurring design strategies, strengths, limitations, and performance patterns across the three case studies. Comparison between the PEM results and environmental simulation outcomes helped to determine which characteristics improve the comfort, daylight availability, natural ventilation, flexibility, and the wellbeing of users. These findings were then integrated with established biophilic design principles and the requirements of temporary healthcare facilities to develop the BMMHU framework. Design strategies with high levels of environmental performance and feasibility were included into the framework; on the other hand, the limitations identified in the case studies were dealt with through the modification of the strategies. Therefore, the framework incorporates aspects of modular construction, biophilia, performance, and spatial flexibility in order to come up with a solution that is both resilient and supportive of human health.

4. Case Study Analysis

4.1 Detailed evaluation of three international cases

This paper critically reviews three existing micro-modular emergency architectures. These cases demonstrate various approaches to rapid deployment, modular construction and humanitarian response. The evaluation framework developed from the literature review was applied to analyse each case to evaluate its environmental performance and architectural performance.

4.1.1 UNHCR/IKEA Better Shelter

Better Shelter is a flat-packed steel and polymer system modular emergency shelter, developed by the Swedish social enterprise Better Shelter with the United Nations High Commissioner for Refugees (UNHCR) and the IKEA Foundation. It was developed to offer displaced populations a safer and more durable alternative to traditional emergency tents when it was launched in 2015. Better Shelter is better than the temporary canvas tents that are used for a short time (Goulding & Rahimian, 2019). It is built to last about 3 years which makes it ideal for long humanitarian crises where displaced communities often live-in camps for long times. It is designed for use in recovery, healthcare and education contexts. The regular Better Shelter unit offers roughly 17.5 m² of enclosed floor space. The shelter is can be transported efficiently and assembled on-site using simple hand tools without requiring specialized construction skills. A standard unit can normally be assembled by four people in about four to eight hours, depending on the experience of the assembly team and site conditions. The frame is made of lightweight galvanized steel, and is covered in polyolefin plastic panels that provide weather protection, but keep the weight low and make it easy to transport (Scott-Smith, 2019). Its solar lighting and ventilation systems represent an early, functional biophilic gesture, improving air quality and occupant dignity relative to canvas tents. But this is where the trade-off begins. The polymer skin that makes fast flat-pack assembly possible also contributes to poor thermal performance in hot climates. Moreover, its combustible nature increases fire risk in densely populated camp settings. Therefore, it does not provide the thermal insulation, airtightness or fire resistance required for infection-sensitive healthcare environments or for use in extreme weather conditions (Facchetti, 2021).

4.1.2 Paper Partition System (PPS-4)

Japanese architect Shigeru Ban has designed the Paper Partition System (PPS), an emergency interior partitioning system for disaster evacuation centres to enhance privacy, dignity and psychological well-being (Ban et al., 2022). PPS 1 was first launched and developed in 2004 in response to the Niigata Chuetsu Earthquake in Japan. But it received significant recognition after being deployed to 50 evacuation centres during the Great East Japan Earthquake. It has since been used in a number of disaster relief operations worldwide, including earthquakes, floods and the COVID-19 pandemic. The PPS, unlike traditional emergency shelters that prioritize physical safety, caters to the often neglected social and emotional needs of the displaced by providing private living spaces within large communal buildings like gymnasiums, schools, and exhibition halls (Łątka & Morales-Beltrán, 2023).

The PPS is not a stand-alone shelter but is designed to convert existing buildings into more humane emergency accommodation. Each section creates a semi-private area to keep families away from each other, but still open and flexible. The system consists of a light framework of recycled paper tubes, connected by simple joints, and closed with fabric or paper curtains (Ban et al., 2022). The parts are cheap, recyclable, easy to transport and require no special tools or building skills. The system is very suitable for rapid disaster response because the partitions can be assembled by volunteers or occupants within a short time. The partitions are modular, so they can be arranged in different configurations to suit different family sizes and available floor space (Diarte & Shaffer, 2021).

PPS clearly demonstrates the trade-off between rapid deployment and infection control. It is not a closed shelter and so it does not provide protection from the weather outside and depends entirely on an existing building for structural safety, thermal comfort and environmental protection. (Łątka et al., 2025). The fabric curtains provide little acoustic insulation and allow noise to pass readily between adjoining spaces. Moreover, while its lightweight construction allows for quick assembly, it lacks the sealed enclosure, moisture resistance, and structural mass required to maintain safe and hygienic healthcare environments.

4.1.3 Connected Units for Respiratory Ailments (CURA)

CURA pods (Connected Units for Respiratory Ailments) are self-contained, modular intensive care units built into repurposed shipping containers. It was released as an open-source project by an international team including Carlo Ratti Associati during the COVID-19 pandemic, and rapidly scaled hospital ICU capacities (Merten et al., 2020).

The system uses a standard 20-foot ISO shipping container and converts it into a fully equipped negative-pressure intensive care room (Witcher, 2020). Shipping containers are a robust, durable and universally available structural module that can be transported by road, rail, sea or air. The containers are compact and portable, but they are equipped with medical equipment, electrical systems, mechanical ventilation, lighting and life-support infrastructure. The system is highly scalable, permitting the linkage of multiple units to form larger field hospitals or to integrate with existing healthcare infrastructure. The window in the CURA Pod acts as a biophilic design element, offering access to natural daylight and visual connections to the external environment. Windows during the COVID-19 pandemic, when patients were isolated for long periods, reduced the feeling of confinement (Chudzinska et al., 2024).

Despite their advantages, CURA Pods have several limitations. The interior volume of a 20-foot container is rather small, and the number of patients and health care staff that can be comfortably accommodated in the unit is limited (Witcher, 2020). This system is more complicated than traditional emergency shelters due to the need for trained medical personnel and specialized equipment for installation and operation. Additionally, the complicated ventilation and medical systems drive up construction and operating costs compared to temporary housing solutions. The steel shipping containers require 1-2 days to assemble, are resource- and cost-intensive and have difficulty with thermal insulation in extreme climates. CURA's daylight strategy is also limited by the container typology itself, apertures are limited to what a structural steel box allows, so biophilic integration is partial, not fully resolved.

4.2 Comparative Analysis of Case Studies

A critical comparison of the three case studies is shown in Table 3, highlighting their differences in purpose, materials, construction time and performance. Better Shelter (2015) is a durable, multi-purpose solution for long-term recovery, offering steel/polymer construction and features such as solar lighting, though it is relatively costly. PPS-4 (Ban, 2018) is lightweight, quick to assemble (under an hour) and made from paper and fabric, making it cheap and suitable for short-term, private shelters. CURA (Ratti, 2020), on the other hand, is designed for healthcare use, especially for infection control and is made of steel and glass; while more expensive and slower to assemble, it provides resilience and access to daylight.

Table 3: Comparative analysis of Better Shelter, PPS-4 and CURA.

Case Study	Better Shelter	PPS-4 (Ban)	CURA (Ratti)
Year of launch	2015	2018	2020
Key purpose	Shelter, healthcare, education, protection	Shelter during flood disaster	Shelter during Covid-19
Primary material	Steel/ polymer	Paper/ fabric	Steel/ glass
Assembly time	4 hours	< 1 hour	1–2 days
Biophilic element	Solar lighting/ ventilation	Tactile/ recycled	Natural light/ views
Best use case	Long-term recovery	Privacy in crowded shelters, suitable for short-term use	ICU/ Infection control
Cost efficiency	Costly and less resilient	Cheap and affordable for mass use	Costly but resilient

5. Performance Evaluation of the Case Studies

This chapter evaluates the climatic, architectural and environmental performance of the selected case studies through simulation and comparative analysis. The findings identify key strengths, limitations and performance gaps, forming the basis for the proposed Biophilic Micro-Modular Healthcare Unit (BMMHU) framework.

5.1 Climatic Comfort and Daylighting Performance Analysis of the Case Studies

Climate Studio was used as the simulation tool to assess overall climatic comfort performance. The weather file selected was Dhaka-Shahjalal.Intl.Ap, DH, BGD to match the local context (23.84°N, 90.40°E, tropical savanna climate (Köppen: Aw), Year: 2004-2018). The simulation of the environment was carried out on 21 June at 12:00 noon. It is the summer solstice, the longest day of the year in Bangladesh, with about 13 h 35 min of daylight. Analyzing the design under the most extreme summer condition ensures that the proposed shelter will perform adequately for the rest of the year. The evaluation was conducted based on three parameters: point-in-time illuminance to measure the amount of light available in a space at a specific time and date; spatial daylight availability (sDA) to evaluate how effectively daylight is distributed throughout the space over the year; and annual glare (sDG) to assess the possibility of visual discomfort caused by excessive brightness or direct sunlight during the year. Table 4 presents a summary of the numerical values obtained from the simulation results.

Table 4. Summary of the simulation results.

Metric	Better Shelter	PPS (Ban)	CURA (Ratti)
Mean illuminance (lux)	11,254	53,163	12,255
Median illuminance (lux)	254	76,622	832
sDA% (≥300 lux, 50% hrs)	29.9%	100%	100%
sDG% [ASE] (disturbing glare)	26%	100%	43.6%

Figure 3 shows the point-in-time illuminance (mean and median illuminance) performance of PPS, CURA, and Better Shelter. PPS showed extremely high illuminance levels, indicated by the red colour, which may create visual discomfort due to excessive brightness. It recorded the highest daylight levels, with a mean illuminance of 53,163 lux and a median illuminance of 76,622 lux. CURA comparatively provided a more balanced daylight distribution with moderate illuminance levels (mean illuminance of 12,255 lux and a median illuminance of 832 lux) across the space. Better Shelter showed lower illuminance levels with a uniform distribution, resulting in comparatively dim indoor lighting. It showed the lowest daylight levels, with a mean illuminance of 11,254 lux and a median illuminance of 254 lux

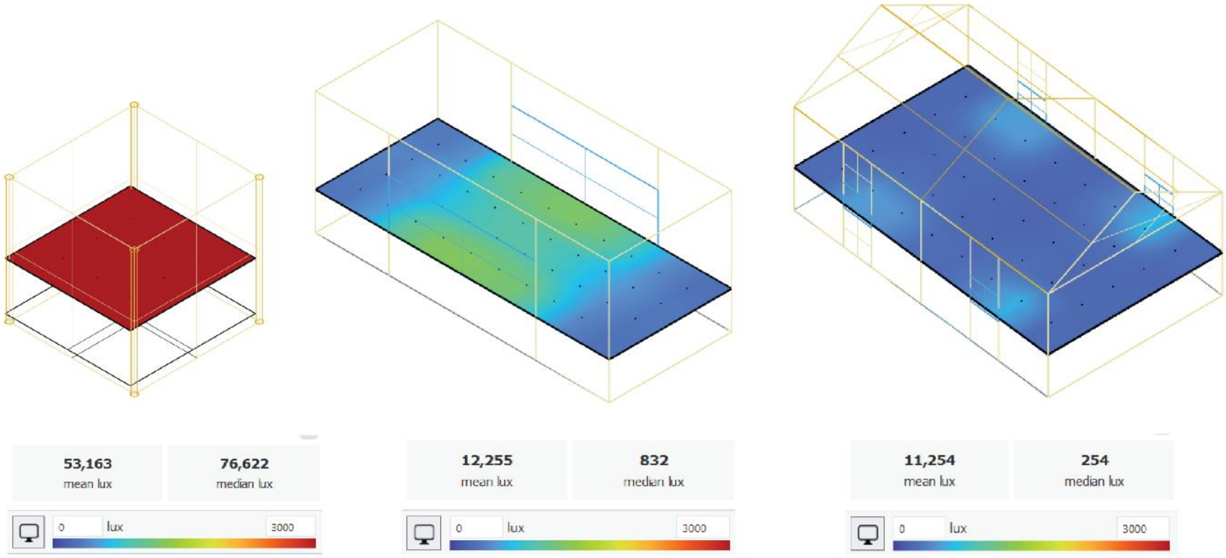

***Figure 2**. Performance in terms of point-in-time illuminance of PPS (left), CURA (middle) and Better Shelter (right)*. (Source: Author, 2025)

The sDA analysis (Figure 4) showed that PPS had the highest daylight coverage throughout the space. A value of 100% sDA, indicating that the entire space received at least 300 lux for 50% of the occupied hours. CURA also performed well (100% sDA) with good daylight distribution near the openings, while Better Shelter had lower sDA (29.9%) due to its smaller openings and enclosed structure.

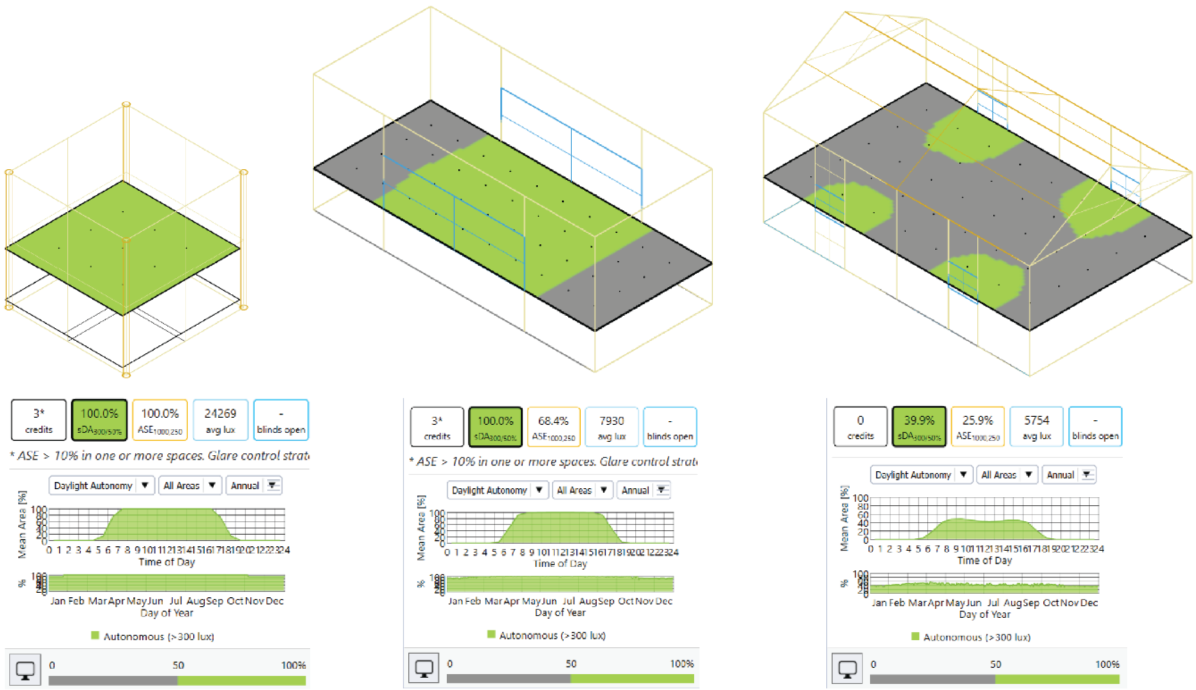

Figure 3. Performance in terms of sDA of PPS (left), CURA (middle) and Better Shelter (right).
(Source: Author, 2025)

The sDG analysis (Figure 5) indicated that PPS experiences the highest glare levels 100% as it has no external shading or protective enclosure. The open partition system allows direct sunlight to enter the space without obstruction, resulting in excessive daylight and severe visual discomfort. CURA shows moderate glare conditions (43.6%), whereas Better Shelter performs better in glare control with comparatively lower glare levels (26.0%).

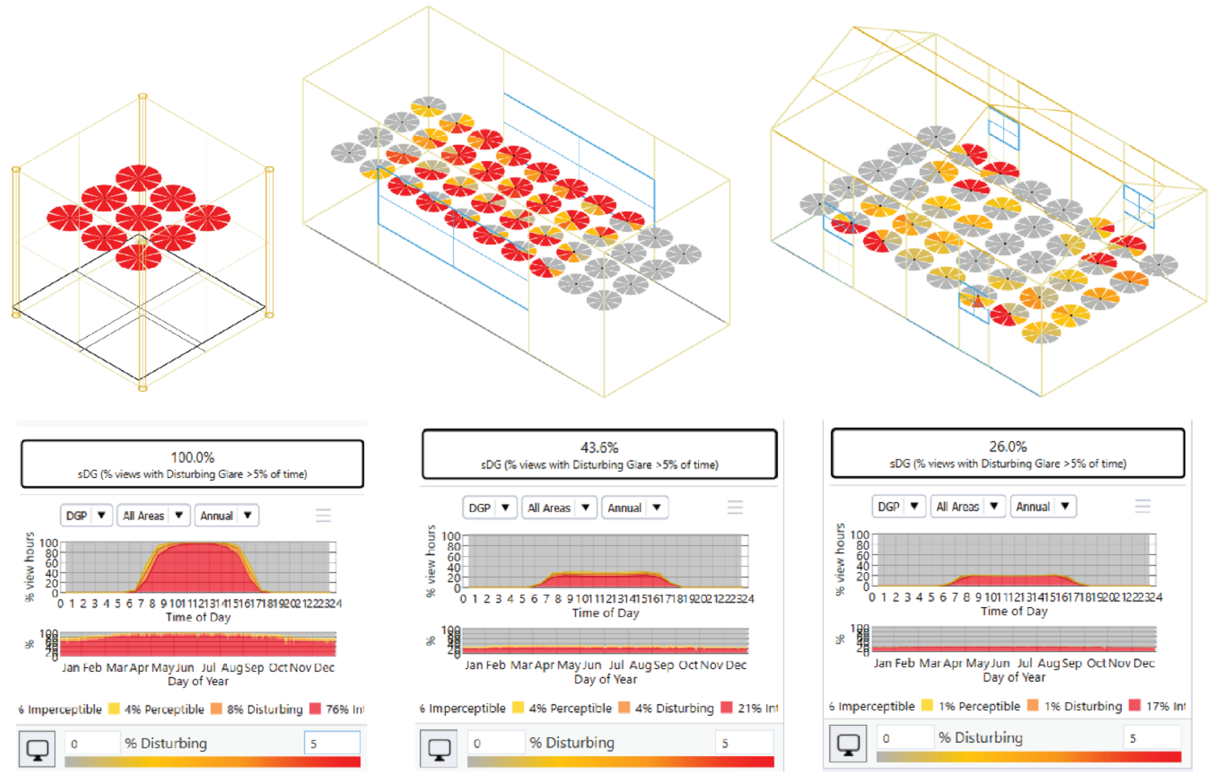

Figure 4. Performance in terms of annual glare of PPS (left), CURA (middle) and Better Shelter (right). (Source: Author, 2025)

Overall, the analysis showed that each case study has different strengths and limitations in terms of daylight performance and visual comfort. The simulation results are interpreted by comparing them with previous daylighting studies, rather than considering the numerical values alone. High daylight availability does not always mean better visual comfort, as excessive daylight can also increase glare. Among the three case studies, PPS achieved the highest sDA, indicating excellent daylight availability. However, it also recorded the highest glare level (100% sDG). This is consistent with previous studies, which show that buildings with little or no external shading often receive abundant daylight but also experience severe glare. Since the PPS has no exterior enclosure or shading elements, direct sunlight enters the space easily, increasing visual discomfort.

In contrast, Better Shelter and CURA Pod use enclosed walls and smaller openings, which reduce glare but also limit the amount of daylight entering the space. These findings demonstrate the common trade-off between daylight and visual comfort. Therefore, daylight performance are evaluated using both sDA and glare metrics (sDG or ASE) rather than relying on daylight availability alone. An effective shelter should provide sufficient natural light while controlling direct sunlight to maintain visual comfort.

5.2 Comparative Evaluation of Architectural and Environmental Performance

Building on the previous discussion in Section 2.5 and the case study analyses presented in Sections 4.1 and 4.2, this section provides a comparative evaluation of the three international case studies. The architectural comparison highlights distinct strengths among the three shelter types (Table 5). PPS performed best in rapid assembly and showed slightly higher spatial flexibility, while CURA excels in infection control and environmental comfort but has a more complex setup. Better Shelter and PPS integrated well in urban contexts, whereas CURA had only moderate compatibility.

Table 5. Architectural performance comparison

Indicators	Better Shelter	PPS	CURA Pods
(i) Spatial adaptability	Moderate	High	Moderate
(ii) Rapid assembly	Moderate	High	Low
(iii) Infection control	Moderate	Low	High
(iv) Environmental comfort	Low	Moderate	High
(v) Urban system integration	High	High	Moderate

The environmental performance comparison shows that CURA performs best in thermal comfort, while Better Shelter performs poorly (Table 6). PPS achieves the highest daylighting adequacy and moderate natural ventilation performance, whereas the other two perform poorly in both. The three shelters demonstrate weak to moderate integration of biophilic elements.

Table 6. Environmental performance comparison

Indicators	Better Shelter	PPS	CURA Pods
(i) Thermal comfort	Low	Moderate	High
(ii) Daylighting adequacy	Moderate	High	Moderate
(iii) Natural ventilation	Low	Moderate	Low
(iv) Integration of biophilic elements	Low	Moderate	Moderate

5.3 Performance gap analysis

From the radar chart in Figure 6, we can see the overall performance of the three systems. PPS demonstrated the most balanced and consistent performance across most indicators, particularly excelling in adaptability, rapid assembly, and daylighting. CURA, on the other hand, performed well in healthcare-related areas such as infection control and thermal comfort, making it more suitable for medical emergency use. Better Shelter appears to be the most basic solution, with some strengths in urban integration but generally weaker performance in environmental comfort and ventilation. Overall, PPS emerged as the most versatile option, while CURA was specialized for healthcare, and Better Shelter served as a simple but less efficient alternative.

The gap analysis makes the argument viscerally clear: no existing precedent reaches "High" across the nine parameters, and fails on biophilic integration. The dashed BMMHU target line represents the framework's minimum performance commitment.

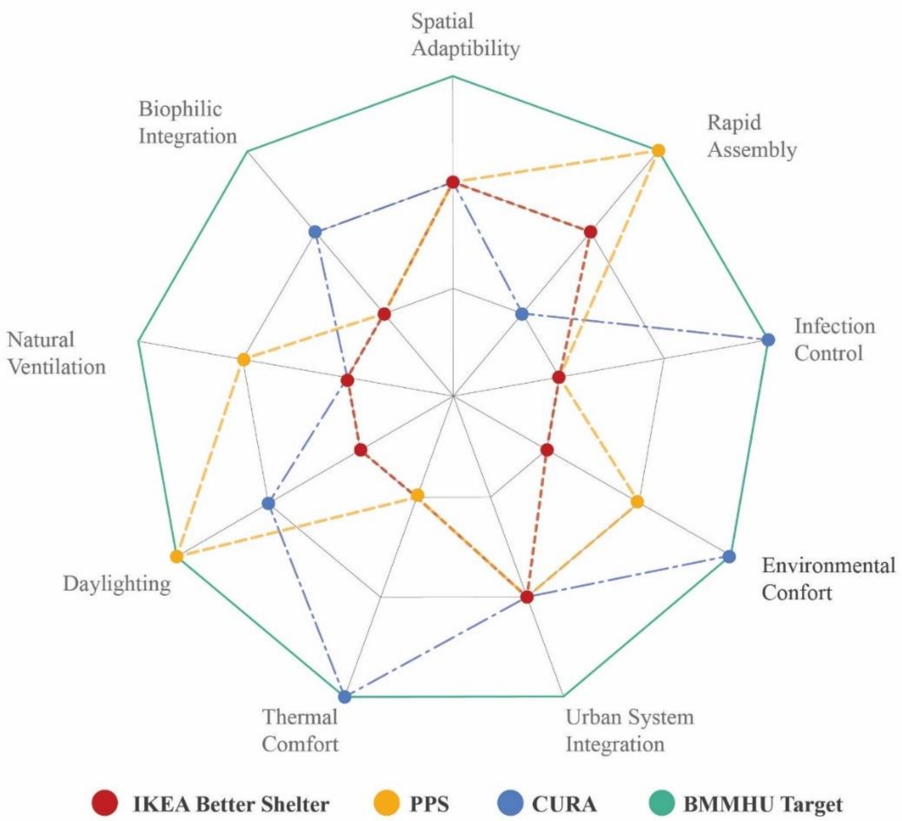

Figure 5. Radar chart comparing the architectural and environmental parameters of the three cases (Source: Author, 2026)

6. The BMMHU framework

The case study analysis, evaluated against the nine-criterion performance evaluation matrix, reveals a consistent deficit across the three precedents: no existing system achieves simultaneous excellence in emergency clinical function, spatial adaptability, rapid assembly, and biophilic or salutogenic integration. This gap is confirmed against published peer-reviewed research and standards in practice. Based on this evidence base, five cross-cutting design principles were distilled, extracted from the convergence of theoretical standards and demonstrated performance gaps. These principles are operationalized through a three-tier framework , each governing a distinct scale of the module's performance, which defines the Biophilic Micro-Modular Healthcare Unit (BMMHU) framework. (Figure 7).

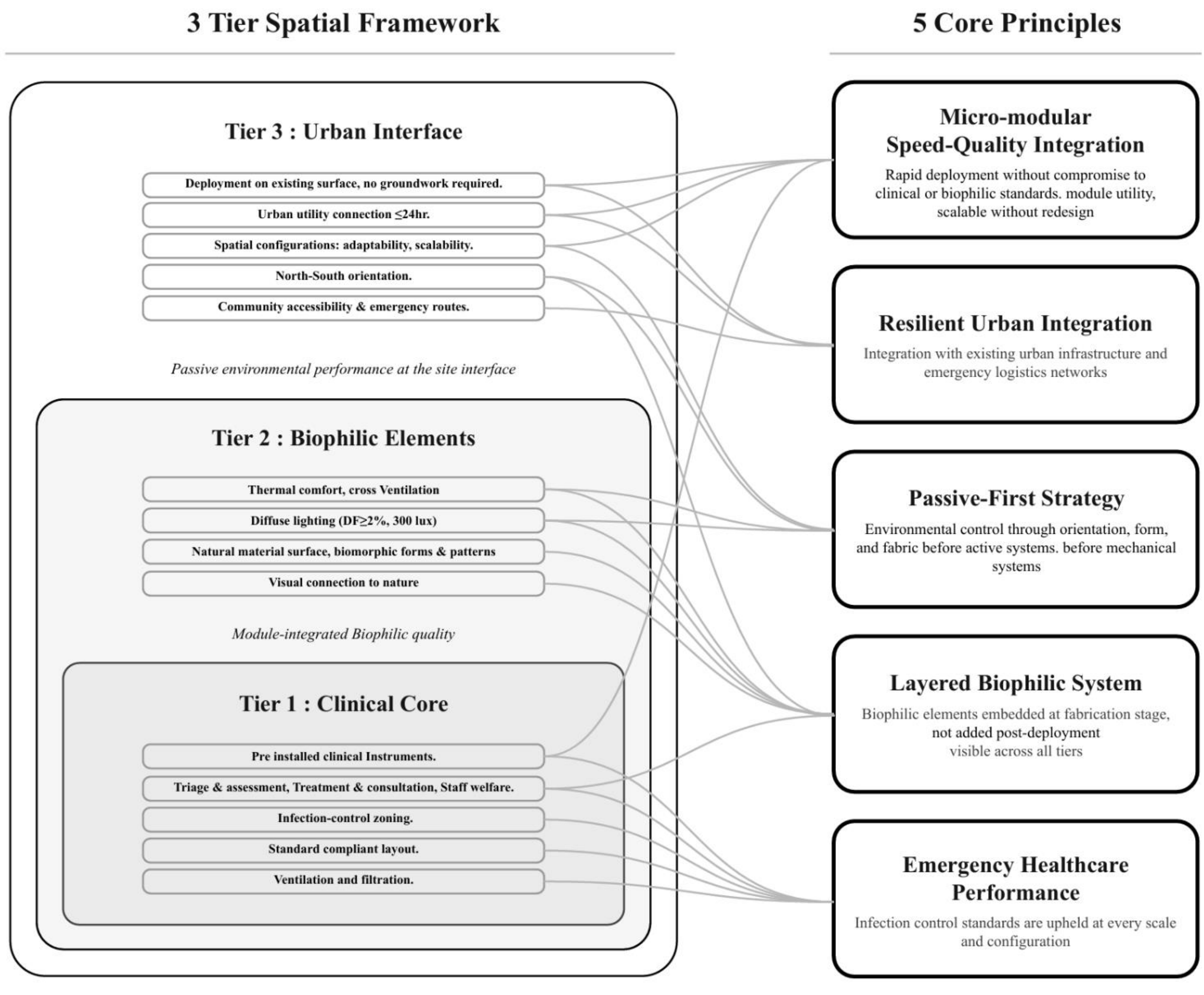

Figure 6. The 3-tier BMMHU Framework, governed by 5 core principles. (Source: Author, 2026)

6.1 Three-tier spatial framework

The tiers function as a nested delivery system rather than independent layers. Tier 1 locks in the clinical baseline that cannot be compromised, regardless of site conditions or configuration. Tier 2 executes biophilic and passive strategies at the fabrication stage. Tier 3 determines which passive strategies are physically possible, eliminating the on-site time penalty associated with emergency response.

Tier 1: Clinical Core established the non-negotiable clinical baseline. WHO (2021), ASHRAE 170 (2021), ASHRAE 55 (2020), CIBSE (2015) compliance layout, Infection control zoning, ventilation and pre-installed instruments ensure the module is operationally ready within hours of arrival, without dependency on local infrastructure. Spatial adaptability at this tier allowed the module to be reconfigured for triage, treatment or isolation without modification.

Tier 2: Biophilic Envelope/Elements is the environmental quality layer. Daylighting, cross-ventilation, natural material and visual connections to nature are factory-integrated before deployment, making biophilic performance a fabrication commitment rather than a site decision. This tier treated environmental quality not as comfort, but as a clinical variable that directly influences recovery time, anxiety levels and staff performance.

Tier 3: Urban Interface/Integration governs how the module is deployed within the city. It establishes site orientation, access, flood clearance and rapid utility connections in alignment with WHO (2021), ASHRAE 170 (2021), ASHRAE 55 (2020), CIBSE (2015), FEMA (2021) standards, without requiring permanent foundations or groundwork. Decisions at this tier determined what Tier 2 can achieve without mechanical assistance, particularly orientation, solar exposure and surrounding urban density, which directly shape the passive daylighting and ventilation performance of the system.

6.2 Five core design principles

The five principles formed the backbone of the three-tier framework. Speed, quality, and clinical performance integrity ensure the framework never sacrifices function for speed or aesthetics. A passive-first strategy and layered biophilic delivery ensure that environmental quality is structurally embedded rather than added on. Resilient urban integration ensures that the entire framework functions under disrupted urban conditions.

Micro-modular speed-quality: Drawing on the consistent speed-quality trade-off, modular units should meet clinical and biophilic standards simultaneously, without trading one for the other.

Resilient urban integration: This principle requires the module to rapidly anchor in existing urban infrastructure, functioning in disrupted or seismically at-risk contexts without permanent groundwork.

Passive-first strategy: Environmental control should be achieved through orientation, form, and fabric before any active mechanical system is introduced.

Layered biophilic delivery: Nature-based design should be embedded across all three tiers: Clinical Core (Tier 1), Biophilic Elements Integration (Tier 2), and Urban Interface (Tier 3).

Clinical performance integrity: WHO EMT, ASHRAE 170, and infection-control standards are upheld at every scale and configuration, treating environmental quality as a clinical variable rather than a comfort add-on.

7. Discussion

7.1 Interpretation of Key Findings

The study addressed three questions: the criteria for temporary healthcare units to enable clinical function and psychological well-being; the patterns of gaps in existing precedents; and how biophilic quality can be integrated without delaying deployment. The nine-criterion Performance Evaluation Matrix (PEM) and Dhaka-based simulations answered these clearly. None of the three precedents achieved a "High" rating across all criteria, with the weakest performance consistently occurring in environmental and biophilic criteria (E1–E4). This confirms the integration deficit identified earlier: current temporary healthcare designs address clinical, logistical, and environmental performance as separate priorities rather than as an integrated system.

The shortcomings were systematic rather than random. Environmental comfort, natural ventilation and biophilic integration, all factors closely associated with recovery, stress reduction and staff performance, were consistently compromised. Each case optimized one aspect at the expense of others: PPS offered rapid deployment and abundance of daylight but no enclosure and glare control; CURA offered infection control and thermal comfort but was more expensive and time-consuming to assemble; Better Shelter integrated well in urban settings but did not perform well in ventilation and environmental comfort. These findings suggest that the speed–quality trade-off is embedded in current design approaches.

Simulation results further showed that high daylight availability does not guarantee visual comfort. PPS achieved 100% sDA but also 100% disturbing glare due to the absence of shading, whereas Better Shelter and CURA reduced glare but limited useful daylight. Effective daylighting therefore requires balancing both availability (sDA) and glare (sDG). The proposed BMMHU framework responds by embedding environmental quality into the deployment process: Tier 1 establishes the clinical baseline, Tier 2 integrates biophilic and passive strategies during fabrication, and Tier 3 optimizes site conditions for passive performance. This shifts environmental quality from an optional site-level addition to a manufacturing commitment.

7.2 Comparison with Previous Studies

The findings support previous research indicating that buildings without external shading offer plenty of daylight but often lead to severe visual discomfort, and support the links between environmental quality, recovery and well-being established by Joarder and Price (2013), Ulrich et al. (2008), Al Khatib et al. (2024), Golembiewski (2022) and Tekin et al. (2023). However, this study differs from most previous research in that it applies these principles to temporary rather than permanent healthcare facilities (Ackley et al., 2024).

The study also strengthens the evidence that temporary healthcare facilities are frequently used beyond their expected lifespan (Cerrahoğlu & Maden, 2024; Ma & Chen, 2025), making environmental quality a necessity rather than an optional feature. While earlier modular construction research primarily emphasized speed, cost, and transportability (Abbasi et al., 2024), this study places environmental and biophilic performance alongside clinical and logistical criteria within a unified evaluation framework, bridging previously disconnected research on biophilic design, emergency healthcare, and modular construction.

7.3 Strengths and Limitations

The strength of this study is the integrated approach. The PEM combines clinical, logistical and environmental performance within a single framework from published standards and top tier peer-reviewed research, making the assessment transparent and repeatable. This matrix is augmented with daylight and glare simulations from Dhaka to provide objective evidence of the environment. The BMMHU framework translates the results into a staged implementation strategy.

Several limitations remain. The analysis included only three case studies and two reviewers, so agreement reflects consistency rather than statistical reliability. The ordinal low–moderate–high scale identifies relative strengths and weaknesses without weighted scoring. Simulations were limited to daylight and glare, excluded surrounding context to maintain consistent boundary conditions, and were not field-calibrated because the precedents are located abroad. The thermal and ventilation performance were based on literature rather than dynamic simulation, and the BMMHU framework has not been tested through real-world implementation.

7.4 Implications and Future Directions

The results show that biophilic quality can be integrated into temporary healthcare units without delaying deployment if incorporated during fabrication. The proposed staging strategy provides a real-world road map: establish the clinical baseline, embed passive and biophilic features during manufacture, and optimize site conditions to maximize environmental performance. Other evaluation criteria besides the speed of deployment and the number of beds for EMT standards, such as performance in environmental and psychological aspects, should be included in the policy level.

Future research should validate the BMMHU framework with the development of a full-scale prototype and post-occupancy evaluation measuring patient recovery, stress and staff performance. Environmental validation would be improved by field measurements that support dynamic thermal and airflow simulations. Increasing the number of case studies and reviewers, and exploring the possibility of weighted scoring, would improve the reliability of the PEM; testing the framework in different climates and disaster contexts would also evaluate the wider applicability of its passive-first design approach.

8. Conclusion

This study developed and applied a nine-criterion Performance Evaluation Matrix to three temporary healthcare precedents and used Dhaka-based simulations to test their daylight and glare performance. No existing system performed well across all criteria, and the clearest weaknesses lay in environmental comfort, natural ventilation, and biophilic integration. Each precedent excelled in one area while failing in others, confirming a built-in trade-off between speed, clinical function, and environmental quality. The simulations further showed that abundant daylight does not guarantee visual comfort, as unshaded designs suffer severe glare.

The BMMHU framework addresses these gaps by organising performance into three tiers — clinical core, biophilic elements, and urban interface — governed by five design principles. Its central contribution is treating environmental quality as a clinical variable and a fabrication commitment rather than an optional, on-site addition. This offers designers a practical route to combine rapid deployment with biophilic quality, and gives policymakers a reason to broaden emergency healthcare standards to include environmental and psychological performance.

The conclusions rest on three case studies rated by two reviewers, so they reveal consistent patterns rather than statistically reliable measures. The simulations covered daylight and glare only and were not field-calibrated, and the framework itself remains conceptual and untested in a real deployment.

Future work should construct and evaluate a physical BMMHU prototype, add full thermal and ventilation simulation with field validation, and expand the evaluation to more cases, reviewers, climates, and disaster types. These steps would confirm the framework's real-world performance and support its adoption in emergency healthcare planning and policy.

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Conflicts of Interest

The Authors declare that there is no conflict of interest.

Data availability statement

The data supporting the findings of this study were generated through literature review, case study analysis, and simulation-based evaluations. All relevant data and references are included within the manuscript. No additional external datasets were used or are available.

Institutional Review Board Statement

Not applicable.

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