PORTABLE ARCHITECTURE ASPECTS IN THE DESIGN OF EMERGENCY SHELTERS FOR EVACUATION DURING THE ERUPTION OF MOUNT SEMERU

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ABSTRACT

Indonesia's position along the Ring of Fire renders it highly prone to volcanic eruptions, often causing significant displacement and damage to settlements. These conditions highlight the need for effective emergency shelters. However, static emergency shelter solutions, such as conventional tents, are often inadequate for the dynamic evacuation contexts of volcanic disasters. These shelters are typically difficult to transport, slow to deploy, and dependent on skilled labor, resulting in delayed protection for evacuees. This study aims to develop design criteria for portable emergency shelters by applying the principles of portable architecture—mobility, compactibility, lightweight materials, and ease of assembly—to better support evacuation mobility and post-disaster needs. Employing a qualitative descriptive method, the research integrates contextual analysis of Semeru's eruption characteristics with theoretical frameworks of portable design. Data were collected through literature review, design document analysis, and secondary disaster data, focusing on evacuation dynamics, environmental conditions, and ergonomic requirements. The findings identify three essential design aspects: rapid deployment, compactness, and transportability. The proposed shelter design incorporates retractable and folding systems allowing rapid assembly by non-expert users within five to ten minutes, compact packaging for efficient storage, and lightweight construction suitable for motorcycle transport. This design improves response speed and reduces logistical dependence during disaster evacuation. The study concludes that integrating portable architectural strategies into emergency shelter design enhances adaptability, responsiveness, and independence of affected communities, providing not only physical protection but also supporting the continuity of mobility and dignity during prolonged displacement.

Keywords: *Portable Emergency Shelter, Portable Architecture, Volcanic Disaster Evacuation, Rapid Deployment Design, Adaptive Disaster Housing*

INTRODUCTION

Indonesia is highly vulnerable to geological disasters, as it sits between four major tectonic plates: the Eurasian, Indo-Australian, Philippine, and Pacific. Due to this, a lot of seismic activity occurred, causing earthquakes, tsunamis, and volcanic eruptions (Badan Nasional Penanggulangan Bencana, 2021). Volcanic eruptions are among the most destructive natural hazards, often leading to cascading effects on housing, livelihoods, and the well-being of communities (Kamila *et al.*, 2026). Volcanic eruptions exhibit diverse characteristics in terms of scale, processes, and eruptive styles, resulting in a wide range of impacts from localized destruction to global disturbances (Malawani *et al.*, 2021). Consequently, the type and severity of hazards and the appropriate disaster response are strongly influenced by eruption dynamics, which may vary even within a single eruptive event (Cassidy *et al.*, 2018). Semeru is characterized by rapid, repetitive and destructive explosions (Meidinata, 2021), requiring immediate evacuation due to the unpredictable and uncertain nature of eruption development (Griggs, 2017). During the 2021 Mount Semeru eruption, two villages were buried by volcanic ash (Baskoro, 2021), and 10.395 residents were displaced (Mufarida, 2021), highlighting the severe impact on affected communities.

Providing emergency shelter is crucial to ensure the safety and survival of evacuees during the evacuation and emergency response phase (Sphere, 2018). However, static emergency shelter approaches—such as tents or temporary structures at evacuation points—often fail to meet the needs of communities who must continually relocate in response to evolving disaster conditions and shifting safety zones. In addition, these shelters are often hard to transport across difficult terrain and usually rely on external responders for delivery and installation. As a result, static shelters tend to have limited mobility, require longer distribution and installation times, often arrive late in the evacuation process, and frequently depend on skilled personnel for installation (Pusat Studi Adaptasi dan Resiliensi Desain Lingkungan Universitas Katolik Parahyangan (CAREDs), 2018), making them less responsive to rapid changes in evacuation locations.

Previous research in disaster architecture has examined emergency shelter design from various perspectives. Several studies have focused on ergonomics, physical comfort, and the provision of basic human needs in emergency shelters, such as spatial dimensions, circulation, ventilation, and privacy (Davis, 2015; Ramadhani, Dinapradipta and Ekasiwi, 2023). This approach contributes to improving the quality of temporary housing for refugees by placing humans at the center of design. Another approach highlights structure and construction (Nugroho *et al.*, 2011), material sustainability (Widyarko *et al.*, 2021), material efficiency, poverty, and costs in post-disaster shelter (Corsellis and Vitale, 2005). Most of these studies consider shelters as a fixed component of housing and have not clearly linked them to dynamic evacuation systems.

In emergency architecture, portable architecture is increasingly being considered as a relevant design strategy in crisis situations, emphasizing modularity, ease of transport, speed of assembly, and deployment (Kronenburg, 2003, 2008). The portable approach is considered capable of supporting rapid response in emergency situations, both as temporary housing and supporting evacuation facilities (Smith, 2011). However, the application of these principles, particularly to the design of transport shelters integrated with the evacuation process during an eruption disaster, has received relatively little research in the Indonesian context.

Furthermore, the long-term relocation program to permanent housing (*huntap*) has become a government solution to reduce the risk of housing in disaster danger zones. However, recent studies have shown that this relocation program does not always run smoothly. A study was conducted in Mount Semeru disaster area, "Factors influencing return migration after disaster relocation," found that two main factors—dissatisfaction with permanent housing facilities and emotional attachment to the place of origin—contributed to the intention to return to the old settlement after relocation. The housing dissatisfaction factor indicates that the inappropriate design and accessibility of the *huntap* resulted in dissatisfaction among residents, while place attachment attracted them to return to their original place despite the risks they will face further. The results of this study explain that relocation policies that are too technical without considering socio-cultural factors have the potential to fail in the long term (Kamila *et al.*, 2026).

Figure 1. Residents Returned to Their Original Affected Homes Rather Than Living in *Huntap*
Source: Chandra, 2025

Disaster relief shelters should be designed to respond to natural and human-made disasters, providing temporary yet resilient housing solutions for affected communities (Smith, 2011). Within the post-disaster context, considerations on local and cultural aspects are crucial to ensure quality of life; therefore, response paradigms cannot rely solely on universal or generalized standards that are not contextually grounded (Potangroa, 2016). The phenomenon of return migration in the Semeru disaster area shows that post-disaster housing solutions have not fully addressed the social, emotional, and cultural needs of the communities. This opens an important research area in disaster architecture studies: not only how shelters are designed and located, but also how emergency shelters and housing can support the mobility flows and needs of communities during and after evacuation, thus not only offering temporary shelter but also reflecting post-disaster social dynamics.

With this background, this study explores the potential of portable architectural strategies in designing portable emergency shelters that are appropriate for the context of Mount Semeru eruption. More specifically, this study examines the applicability of portable architectural aspects in responding to both dynamic disaster conditions and the socio-cultural characteristics of the affected communities. Different from previous studies that emphasize ergonomics and user comfort, this study focuses on the shelter's portability features—mobility, modularity, lightweight materials, ease of installation and dismantling, and functional flexibility—and how these features are relevant in the context of evacuation and complex post-evacuation dynamics, including the phenomenon of relocation and resettlement intentions.

The contribution of this research is twofold: theoretically, it provides a deeper understanding of the application of portable architecture principles in the context of mobile shelters; practically, it serves as a reference for more adaptive, responsive, and humane emergency shelter designs, which consider mobility needs and post-disaster social dynamics such as return migration. This research is expected to broaden the discourse on disaster architecture with a more holistic perspective on the needs of emergency shelters and modern evacuation systems.

THEORY / RESEARCH METHODS

Research Methods

This study employs a qualitative descriptive approach with contextual and theoretical analysis to formulate design criteria for portable emergency shelters in volcanic disaster evacuation contexts. The research aims to understand the relationship between disaster characteristics, evacuation dynamics, environmental conditions, and architectural design strategies that support temporary habitation during emergency situations.

The selection of portable architecture theory is based on its relevance in addressing the limitations of conventional static shelters identified in disaster contexts. Previous studies have shown that many emergency shelters are designed as fixed units and often fail to respond to dynamic evacuation conditions, particularly in situations where affected communities must relocate repeatedly. Therefore, transportable architecture is adopted as a theoretical framework because it emphasizes mobility, adaptability, and rapid deployment, key aspects required to support evacuation processes in volcanic disaster scenarios.

Data collection was conducted through literature review, design document analysis, and secondary disaster data analysis. The literature review was used to identify theoretical foundations related to portable architecture, mobile shelter systems, and emergency housing in disaster situations. Secondary data regarding the characteristics of the Mount Semeru eruption and evacuation conditions were also examined to understand the dynamics of disaster response and the mobility patterns of affected communities.

The collected data were then analyzed through several aspects, including disaster evacuation conditions, site conditions during disaster events, spatial and ergonomic requirements, and the principles of portable architecture. Evacuation analysis examined evacuation routes, the selection of evacuation points, and evacuation time, which influenced the distribution and deployment of emergency shelters. Site analysis considered environmental conditions during disasters, including climate conditions, wind direction, and terrain characteristics that are often uneven or slippery due to volcanic ash. In addition, spatial and ergonomic analysis was conducted to ensure that the shelter can accommodate the basic activities of evacuees during temporary habitation.

Finally, the study analyzed the application of portable architecture principles, including mobility, modularity, lightweight materials and construction, assembly and disassembly systems, and functional flexibility. The results of these analyses were synthesized to formulate design criteria for portable emergency shelters that are responsive to disaster environmental conditions and evacuation mobility. This approach provides a framework for integrating portable architecture principles into emergency shelter design within dynamic volcanic disaster contexts.

The theoretical framework of this study is illustrated in Figure 2. The framework explains the relationship between disaster context, evacuation conditions, and the application of portable architecture principles as the basis for formulating portable emergency shelter design criteria.

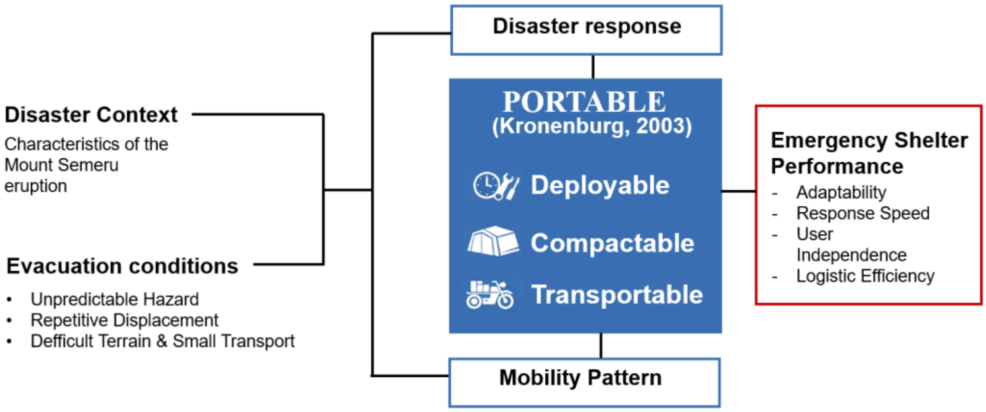

Figure 2. Theoretical Framework

Semeru Eruption Disaster Characteristic

Mount Semeru is located in Lumajang Regency, East Java, Indonesia. Mount Semeru is the highest volcano on Java, with its summit, Mahameru, reaching 3,676 meters above sea level. Compared with other highly active volcanoes in Indonesia, such as Mount Merapi, Semeru is characterized by a high eruption frequency, indicating persistent volcanic activity and continuous hazard potential (Meidinata, 2021; Wardhani, 2021).

The eruption hazards of Mount Semeru include pyroclastic flows, ashfall, lava flows, lahar floods, and volcanic earthquakes. These hazards may occur suddenly, producing rapid-onset disaster conditions that force residents to evacuate immediately from their homes toward safer areas. Consequently, evacuation patterns are often dynamic and repetitive, shaped by fluctuating hazard zones and uncertain eruption durations.

Mount Semeru eruption hazards—including pyroclastic flows, ashfall, lava flows, lahar floods, and volcanic earthquakes—can occur suddenly under unpredictable conditions. Volcanic activity is classified into four levels: Aktif Normal (Level I), Waspada (Level II), Siaga (Level III), and Awas (Level IV), with each level corresponding to expanded restricted zones and evacuation radii (Pusat Vulkanologi dan Mitigasi Bencana Geologi, 2015). At Level I, no restrictions apply within <1 km of the crater; at Level II, restricted areas extend to 1 km from the crater and up to 5 km in hazard-prone directions; at Level III, zones expand to ~5 km, with additional hazards reaching 13–17 km along river channels; and at Level IV, a major eruption is imminent, requiring full evacuation beyond the designated hazard radius. Although eruptions commonly occur from Level III onward, their timing and development remain difficult to predict (Anggraini, 2017), forcing immediate evacuation and creating dynamic, repetitive displacement patterns.

Difficult terrain, long distances to safe locations, and disrupted infrastructure complicates evacuation processes. Affected communities frequently rely on public facilities—such as schools and village halls—as temporary transit shelters before receiving emergency tents distributed by the National Disaster Management Agency (BNPB). However, the limited capacity of sectoral evacuation camps often prevents all evacuees from being fully accommodated, forcing some displaced residents to relocate repeatedly in search of safer refuge (Figure 3). During eruption events, evacuation is restricted to land routes because volcanic ash disrupts air transportation. Ash-covered roads become slippery and difficult for four-wheeled vehicles to traverse, resulting in evacuation mobility that is predominantly dependent on motorcycles and other small-scale transport modes (Figure 4).

Figure 3. Residents Evacuate to Mosque in Pronojiwo District
Source: Aminudin, 2021

Figure 4. Evacuation on Slippery Terrain Using a Motorbike
Source: Ali, 2022; Kurniawan, 2021

These conditions highlight the critical need for disaster emergency shelters that are capable of providing adequate temporary living space throughout the disaster period. Moreover, unpredictable disaster duration and post-disaster recovery processes may require evacuees to occupy emergency shelters beyond the standard emergency phase of approximately 90 days (Santoso, Felecia and Panjaitan, 2016). Therefore, in addition to ensuring mobility and rapid deployment, emergency shelter design must also consider extended usability to support the dignity, safety, and basic living needs of disaster survivors over longer periods of displacement (Sphere, 2018).

Emergency Shelter in Disaster Evacuation

Emergency shelters are temporary protective structures that provide essential living spaces for populations displaced by disasters (Alharthi, 2020). Within the continuum of a post-disaster context, they serve as immediate and short-term solutions by offering basic protection during the time of emergency, before transitioning to temporary shelters that provide protection during the phase before normal living conditions can be restored, typically a few weeks after the disaster (Quarantelli, 1995). Emergency shelters are designed to meet minimum humanitarian standards of living, addressing urgent needs when normal housing conditions have deteriorated or collapsed (Beatini, Rajanayagam and Poologanathan, 2023). During the immediate post-disaster period, they provide safety and security, not only through physical protection, but also by contributing to psychological stability, helping to overcome the feeling of uncertainty during the time of crisis (Félix *et al.*, 2015). These shelters act as secure locations where survivors can avoid further harm while ensuring minimum survival conditions. They provide basic life protection from environmental hazards and secondary risks such as aftershocks, fires, outbreaks, and exposure (Zhao *et al.*, 2017), while also supporting conditions for living with dignity and privacy (Félix *et al.*, 2015). Beyond providing basic protection, it is equally important to consider human aspects in the design of emergency shelters, including ergonomics and anthropometry in shaping the physical dimensions, as well as proxemics and local context in organizing spatial configurations. These considerations ensure that shelters do not only function as protective structures, but also provide environments that are comfortable, healthy, and dignified for their users (Ramadhani, Dinapradipta and Ekasiwi, 2023).

In post-disaster situations in Indonesia, emergency shelters are typically constructed using conventional tents (Figure 5) provided by BNPB (National Agency for Disaster Management), a universal tent system utilizing polyester-based envelope materials with strong fibers that are resistant to water and dust. However, these tents tend to be static and site-dependent, requiring at least eight people to transport, as well as specific skills for assembly. The deployment process involves approximately 22 knock-down steps, indicating a relatively complex setup procedure. Additionally, the setup of these tents typically requires approximately 30–60 minutes and are usually available after 37 hours following the declaration of emergency alert status (BPBD Provinsi Jawa Timur, 2022). In terms of packaging, the tents require specific skills for proper folding to fit into storage crates. In addition, the packaging is heavy and typically requires at least eight people to lift and transport.

Figure 5. BNPB Conventional tents in deployed and packed conditions
Source: Logistik Peralatan BNPB, 2021

These conditions indicate that existing shelter systems remain dependent on centralized logistics and professional assembly, resulting in limited mobility and adaptability. Consequently, they are less responsive to dynamic and rapidly changing evacuation needs, such as in the case of Mount Semeru eruption, where site conditions can change abruptly and require immediate shelter solutions. In this context, the limitations of existing emergency shelter systems highlight the need for a shift towards more adaptive and context-responsive design approaches. Rather than relying solely on standardized and logistically dependent solutions, future emergency shelters should integrate mobility, rapid deployability, and user-centered considerations to better respond to dynamic disaster conditions.

Theory of Portable Architecture

Disaster evacuation shelters in volcanic eruption contexts require adaptive characteristics that enable them to be relocated quickly in response to changing evacuation dynamics. In post-eruption situations, evacuees often need to move from initial emergency shelter points to temporary shelters as safe zones shift and hazard conditions evolve. Therefore, the design of evacuation shelters needs to incorporate the concept of portable architecture, which refers to structures that can be easily moved, distributed, and assembled in dynamic disaster situations.

The concept of portable architecture originates from the theory of portable architecture, which refers to structures designed to be easily installed in locations distant from their place of production and capable of being relocated when necessary. According to Robert Kronenburg, portable architecture refers to buildings that are mobile and can be transported, assembled, and dismantled efficiently (Kronenburg, 2008). In disaster contexts, portable architecture is often associated with temporary housing that supports mitigation and emergency response processes (Kronenburg, 2003). In contemporary perspectives, portable architecture is often understood as functioning similarly to a machine or device: produced at a relatively small scale, capable of rapid installation, and designed according to the activities it supports.

Several previous studies emphasize the key characteristics of portable structures in disaster situations. The discussion of the Magic Box concept by Renzo Piano highlights that portable structures should be rapidly deployable, compact in form, and easily distributed to disaster locations. Meanwhile, Asefi and Sirus (2012) argue that many existing shelters remain difficult and time-consuming to assemble because they rely on heavy materials and rigid geometric configurations that cannot be folded, which complicates transportation. Recent studies have also shown that modular and folding systems can enhance the mobility and distribution efficiency of emergency shelters. A study conducted by (Kusbiantoro, Lesmana and Gunawan, 2024) developed a modular folded house design that can be folded into a compact form, allowing it to be easily mobilized to disaster locations. The shelter is designed to be lightweight and can be assembled by one or two people, while providing basic protection for evacuees from weather conditions. The structural system utilizes a lightweight steel frame with hinged connections, enabling the building to be folded into a more compact box-like configuration to facilitate transportation and distribution to disaster-affected areas. The study also emphasizes the importance of using lightweight and environmentally friendly materials to support the mobility and sustainability of emergency shelters.

Based on these perspectives, portable shelters for disaster situations generally possess three main characteristics: rapid deployment (deployable), efficient compactness and packaging (compactable), and ease of transportation to disaster locations (transportable). Ideally, portable structures can be dismantled into several manageable components to facilitate distribution and relocation (Werner, 2013).

From a logistical perspective, mobility requirements demand structures that are lightweight and compact to ensure transportation efficiency and economic feasibility (Kronenburg, 2003).

To achieve efficient compactness, several structural strategies can be applied in portable architecture, including folding, sliding, bending, or gathering structural elements into a more compact form (Werner, 2013). Packaging systems may take various configurations such as flat-packed panels, cubic modules, or cylindrical forms. The weight and volume of the packaged structure are important considerations because they determine the transportation methods that can be used. In addition, portability is closely related to the system of assembly and disassembly. Portable structures commonly use prefabricated modular components or repetitive elements connected through dry joints or hinge systems, allowing easier installation, dismantling, storage, and relocation (Kronenburg, 2003). Deployment systems may rely on manual operation by users or utilize mechanical mechanisms that allow the structure to expand and stand independently as a self-deploying structure.

In the context of evacuation during the Mount Semeru eruption, transportation becomes a crucial consideration in the design of portable shelters. During evacuation processes, local communities frequently use motorcycles to move themselves, transport valuables, and carry essential goods. Data from Statistics Indonesia indicate that motorcycles represent the most common type of vehicle in Indonesia, making them the most accessible mode of transportation during emergency situations. Overall, the concept of portable architecture provides a framework for designing emergency shelters that are lightweight, compact, easy to assemble, and easy to relocate, enabling them to support evacuation mobility and temporary habitation needs in dynamic disaster conditions.

RESULTS AND DISCUSSION

Design Criteria

The formulation of design criteria for a portable emergency shelter in the context of the Mount Semeru eruption is grounded in both theoretical review and contextual analysis. The urgency of post-eruption conditions—characterized by rapid displacement, uncertain duration of evacuation, and limited logistical infrastructure—demands a shelter system that is not only functional but also adaptive to dynamic field conditions. Therefore, a set of design criteria is required to translate contextual demands into actionable architectural parameters.

These criteria are derived through the interpretation of portable architecture theory—particularly the framework proposed by Kronenburg (2003; 2008)—which defines mobility, deployability, and relocatability as fundamental characteristics of portable structures. By aligning these theoretical dimensions with the specific challenges of volcanic disaster response, this study formulates three primary design criteria: (1) rapid deployment, (2) compactness, and (3) transportability. These criteria are further elaborated as follows.

(1) Rapid deployment, refers to the ability of a structure to transform from a compact state into a functional configuration with minimal time, effort, and technical skill, corresponding to the concept of deployable systems in portable architecture; (2) compactness, represents the principle of compactable structures, where architectural elements can be reduced into minimal volume through folding, retracting, or modular integration to optimize storage and distribution efficiency (Werner, 2013); and (3) transportability, aligns with the concept of *mobility*, in which structures are designed to be lightweight, modular, and compatible with available transport systems (Kronenburg, 2003).

By structuring these criteria based on theoretical dimensions, this study translates portable architecture principles into context-specific design parameters for volcanic disaster evacuation. These criteria reflect the need for a shelter system that is responsive to dynamic evacuation conditions and limited logistical support. Furthermore, this formulation contributes to portable architecture theory by operationalizing its abstract principles into measurable criteria adapted to disaster mobility contexts.

Portable Architecture Aspect

To address the design criteria requirements, the aspects of portable architecture in this study are analyzed through three main parameters: (1) rapid deployment, (2) compactness and flat-packed configuration, and (3) transportability. These parameters represent the operational translation of portable architecture theory into design strategies, where each aspect corresponds to key theoretical principles—deployability, compactability, and mobility—as discussed by Kronenburg (2003, 2008) and Werner (2013).

Rapid Deployment

The aspect of rapid deployment is critical in emergency conditions, where evacuees require immediate protection within a very limited time frame. However, conventional tents often require considerable time for distribution and installation. As identified in Semeru, emergency tents were only able to be erected approximately 37 hours after the emergency status was declared, resulting in delays in providing adequate protection.

In this context, Rapid Deployment is closely linked to ease of deployment, which depends on the simplicity of the construction system. A shelter can only be deployed rapidly if its structural system minimizes assembly steps, reduces reliance on skilled labor, and enables intuitive operation by users. Therefore, this design adopts transformable construction systems that prioritize mechanical simplicity and integrated components, allowing the structure to transition quickly from a compact state to a functional shelter. The use of retractable and folding systems enhances both speed and ease of deployment by reducing assembly complexity and enabling direct transformation rather than conventional construction. Rapid deployment aspects include retractable construction and folding construction.

The retractable system enables rapid deployment through a pull-based mechanism that transforms the structure into its operational form in a single continuous motion. This system minimizes the use of separate components, thereby reducing assembly time and eliminating complex installation procedures. As a result, the structure can be erected quickly with minimal user effort. This construction serves as the primary structural system forming the walls of the shelter (Figure 5), providing the main spatial framework during deployment.

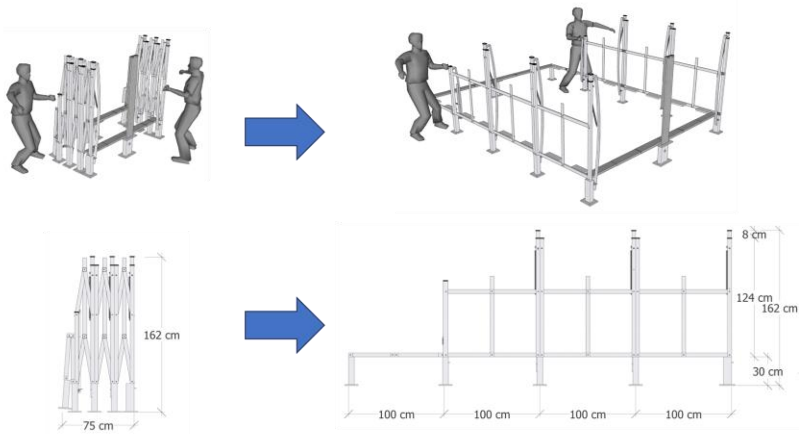

Figure 5. Retractable Construction that can be Compressed and Stretched

Retractable construction also applied to the wall columns (Figure 6), which act as extendable support for the arched roof. These columns use a one-directional (upward) extension with a push-button locking mechanism that automatically secures the structure when extended and can be released when retracted. It is also applied to the floor support beams (Figure 7), which extend linearly without a locking button. This simplifies the operation and contributes to faster deployment.

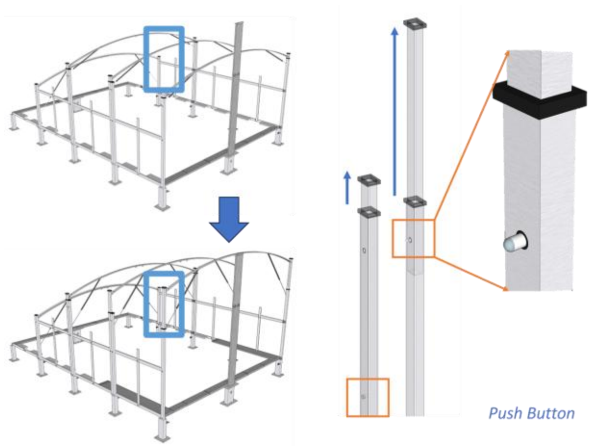

Figure 6. Push-button Locking Mechanism that Secures the Structure in Both Extended and Retracted Positions

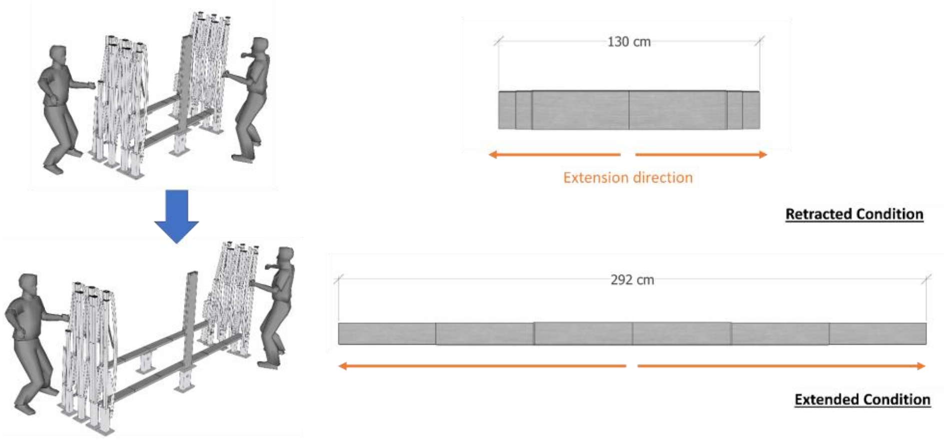

Figure 7. Retractable Floor Beam Extension Mechanism

The folding system employs a hinge-based kinematic mechanism that allows structural elements to transform through controlled rotational movement, reducing assembly stages by enabling direct configuration into their operational position. This system is applied to the floor (Figure 8), and also to both the wall-roof structures of the shelter (Figure 9), allowing simultaneous spatial formation during deployment.

In this system, the horizontal element is initially folded into a vertical position. During deployment, it is extended and automatically returns to a horizontal position with the assistance of a hydraulic spring, ensuring a smooth and low-effort transformation. A hinge and gravity-based locking mechanism secures the folded elements in place during storage, acting as a retainer that maintains stability while allowing quick release for rapid deployment.

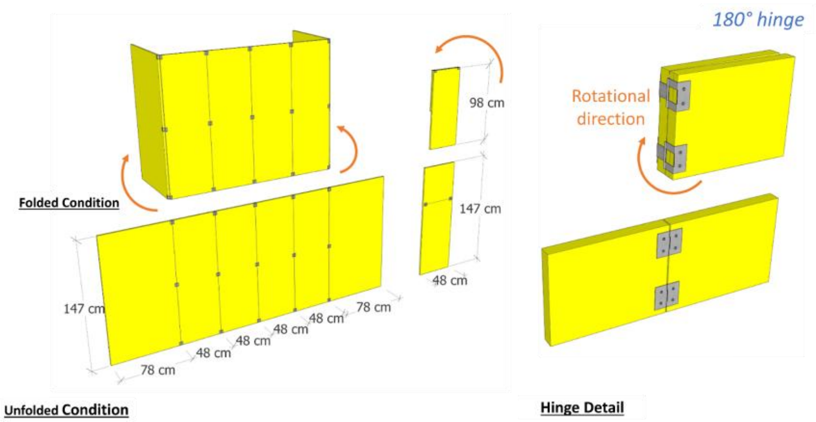

Figure 8. Folded Floor Plate with 180 Hinge

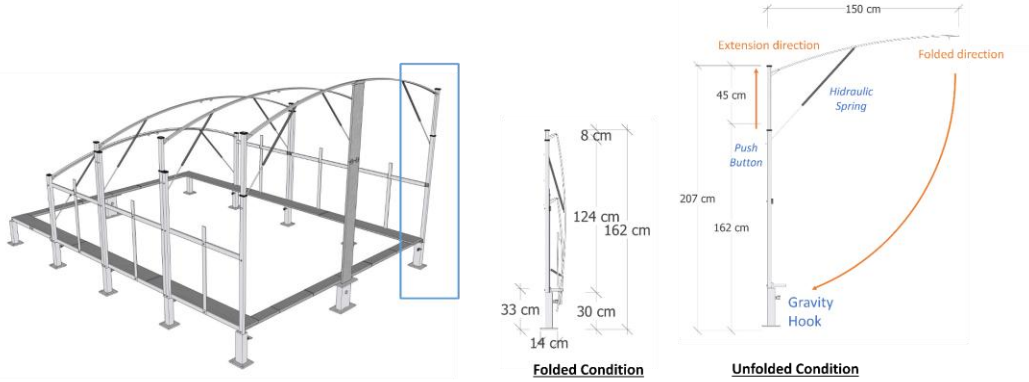

Figure 9. Folding Construction Forming the Roof Structure of the Shelter

The assembly process is designed to be executable by non-expert users, allowing disaster survivors to independently deploy the shelter without reliance on trained personnel. This enables real-time deployment on-site without having to wait for delayed distribution, which can take up to 37 hours in conventional systems. The deployment consists of 8 procedural steps (Figure 10), with an estimated total assembly time of approximately 5–10 minutes, allowing immediate provision of emergency shelter in critical conditions.

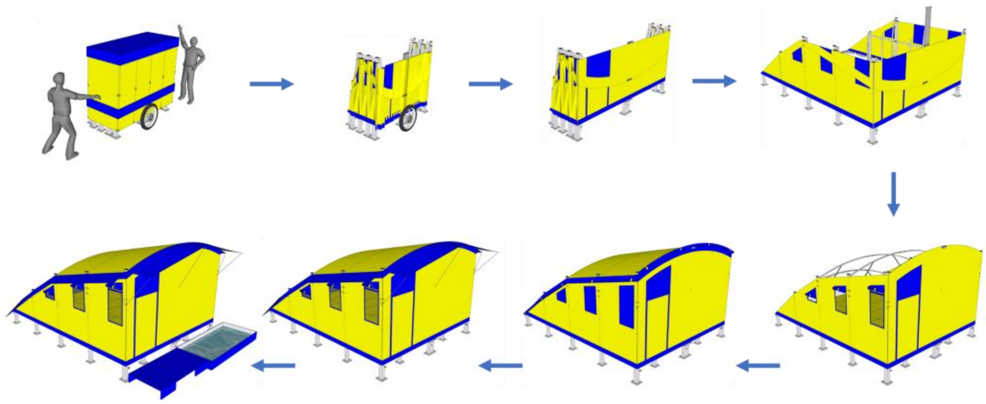

Figure 10. The Assembly Process of Emergency Shelter

Compactness

Compactness refers to the ability of a structure to be reduced to the smallest possible volume for efficient storage and transportation, which is essential in supporting mobility and rapid redeployment in post-disaster conditions. After use, the shelter is re-compacted through a systematic process of folding and reorganizing its components into an integrated packaging system.

In this design, compactness is achieved through the integration of structural and enclosure systems, where the wall enclosure is directly attached to the retractable structure, allowing the folding pattern to follow the movement of the structural frame. This enables an efficient transformation from deployed to compact configuration without requiring disassembly into separate parts. Furthermore, the shelter components are designed with dual functions as both structural and packaging elements, where the floor panels are reconfigured as the walls of the packaging unit, while the terrace and platform components function as the enclosure cover, reducing redundancy and optimizing spatial efficiency.

As seen in Figure 11, after use, the shelter is retracted and reorganized into a compact unit, with the water container functioning as the base of the packaging. The remaining components—including portions of the floor panels, floor beams and bracing elements, roof enclosure, ground anchors, and first-aid equipment—are arranged on top of this base. The HDPE floor panels are then folded upward to form the enclosure walls, secured using fastening elements, while the water container also serves as the top cover, completing the packaging system.

Due to this integrated system, material selection becomes critical. The use of hollow HDPE sheets provides sufficient strength and durability to protect the shelter during storage while remaining lightweight, ensuring that the compacted unit does not impose excessive load during transportation. Finally, the packaged shelter is designed to be directly attached to a motorcycle, enabling efficient and flexible transportation in post-disaster conditions.

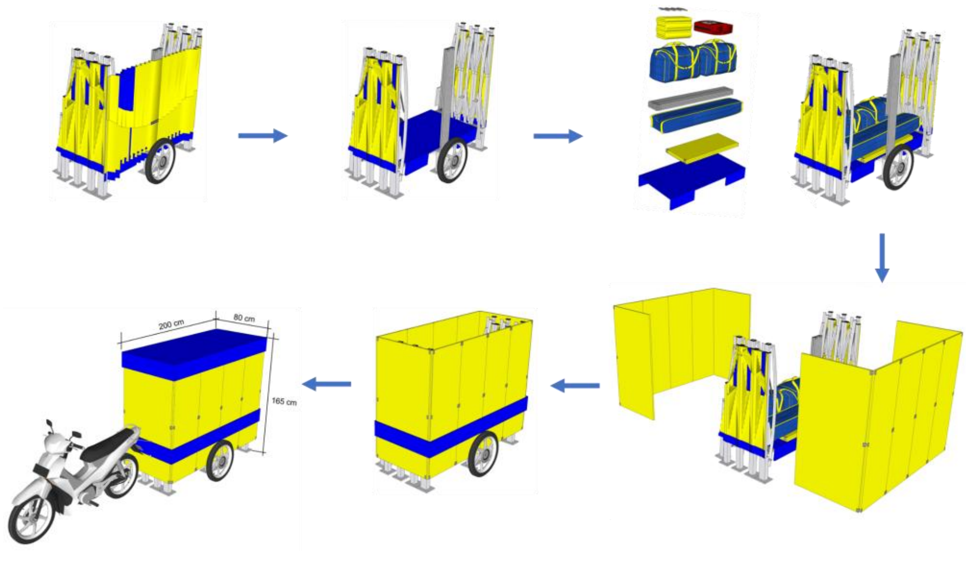

Figure 11. The Packaging Process of Emergency Shelter

Transportability

Transportability refers to the ability of the shelter to be efficiently moved across locations in response to dynamic evacuation conditions. The effectiveness of transportability is achieved through the integration of compactness, lightweight material selection, and a design that allows direct attachment to transportation modes. These factors ensure that the shelter can be relocated quickly and with minimal effort.

In addition to vehicular transport, the shelter is designed to remain manually operable. The total weight and configuration allow the compacted unit to be carried or repositioned by a single adult when necessary. However, the system is primarily optimized for attachment to motorcycles, as motorcycles represent the most dominant and commonly used mode of transportation among local communities during evacuation scenarios. Therefore, utilizing motorcycles as the primary transport mode supports independent evacuation processes and enhances accessibility in difficult terrain conditions.

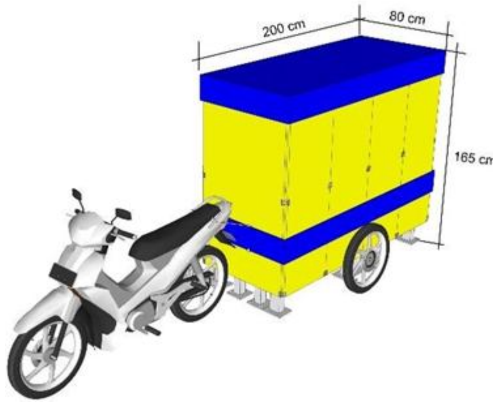

Figure 12. Installation of the Packaged Shelter on a Motorcycle

To respond to this context, the shelter packaging is equipped with an integrated wheel system. The compacted shelter can be attached to the rear of a motorcycle (Figure 12) and transported similarly to a small trailer. The addition of wheels reduces friction and physical effort, enabling smoother movement both when pulled by a motorcycle and when manually handled by users. Furthermore, the wheeled packaging system allows flexibility during deployment. The shelter can be easily repositioned on-site prior to installation, ensuring that users can adjust its placement according to ground conditions and spatial requirements at the evacuation location.

Discussion

This study demonstrates that the application of portable architecture principles, particularly as conceptualized by Kronenburg (2003, 2008) regarding mobility, deployability, and relocatability, provides an effective approach for designing emergency shelters in volcanic disaster contexts, particularly in the case of the Mount Semeru eruption. The integration of three main aspects—rapid deployment, compactness, and transportability—directly reflects the core theoretical dimensions of portable architecture, specifically deployable systems, compactable structures, and mobile units (Kronenburg, 2003; Werner, 2013). These aspects enable the shelter to respond to dynamic evacuation conditions characterized by uncertainty, mobility, and limited infrastructure.

The findings show that the use of retractable and folding construction systems, combined with lightweight materials and integrated packaging, allows the shelter to be rapidly deployed by non-expert users, compactly stored after use, and easily transported using locally accessible modes such as motorcycles. This finding empirically supports prior theoretical arguments that portable architecture should minimize assembly complexity and reduce dependence on skilled labor through integrated and transformable systems (Kronenburg, 2008; Asefi and Sirus, 2012).
In comparison to conventional emergency shelters as seen in Table 1, which are typically static, require centralized distribution, and depend on skilled labor, the proposed portable shelter demonstrates a more flexible and decentralized response capacity that aligns with real-time evacuation dynamics. This distinction is further illustrated through the following comparison:

Table 1. Comparison of Conventional Tents vs Portable Emergency Shelter

No	Aspect	Conventional Tents	Portable Emergency Shelter
1	Deployment Time	±30-60 minutes	5-10 minutes
2	Deployment Step	22 steps (knock-down)	8 steps (retractable)
3	Availability	37 hours after emergency	In real-time disaster
4	Assembly	≥8 skilled laborers	1-2 non-expert users
5	Packaging	Bulky, non-compact	Compact, foldable, integrated
6	Mobility	Static, site-dependent	Highly mobile, follows evacuation flow
7	Transportation	Truck-based logistic	Motorcycle-compatible transport
8	Adaptability	Fixed location	Relocatable, support repeated evacuation
9	Dependency	Reliance on external aid	Support independent evacuation

This comparison indicates that the proposed portable shelter is not merely a design variation, but a systemic shift from centralized, static shelter provision toward decentralized, user-driven deployment. Compared to conventional static shelters, this approach significantly improves response time, reduces dependence on centralized logistics, and supports independent evacuation processes.

Beyond these improvements, the study highlights that emergency shelter design should not only focus on protection and habitability, but also on mobility and adaptability as essential parameters in disaster response. This expands the theoretical discourse of emergency shelter design, which has traditionally emphasized ergonomics and habitability (Davis et al., 2015; Ramadhani et al., 2023), by positioning mobility as a primary design variable rather than a secondary logistical consideration.

In relation to portable architecture theory, this research contributes by contextualizing its principles within a volcanic disaster evacuation framework, where mobility is not optional but essential due to shifting hazard zones and repetitive evacuation patterns. While previous studies have discussed portability in terms of structural efficiency and prefabrication, this study extends the theory by integrating evacuation behavior, local transportation systems (motorcycles), and socio-spatial dynamics into the architectural design process.

By aligning architectural design with evacuation dynamics and local conditions, portable shelters can function as adaptive infrastructures that support both immediate survival and continuous displacement during disaster events. Accordingly, these advantages highlight the potential of the design in increasing responsiveness, accessibility, and user autonomy during disaster situations. However, this approach also presents several limitations, including the lack of real-world prototyping and testing, uncertainty regarding structural performance under extreme environmental conditions such as heavy ashfall or strong winds, and potential constraints in spatial capacity for long-term occupancy.

CONCLUSIONS

This study confirms that the application of portable architecture principles provides a context-appropriate approach for emergency shelter design in volcanic disaster evacuation. Within this approach, portable architecture is positioned as a specific operational strategy that emphasizes relocation and mobility in dynamic evacuation contexts. The integration of rapid deployment, compactness, and transportability enables shelters to respond effectively to uncertainty, repeated displacement, and limited infrastructure. The findings demonstrate that transformable systems—such as retractable and folding mechanisms—combined with integrated packaging significantly enhance deployment speed and reduce logistical dependency.

This research contributes theoretically by operationalizing portable architecture principles into measurable design criteria for disaster mobility contexts, and by reframing shelter as part of an evacuation system rather than a static object. Practically, it provides a design reference for developing lightweight, user-deployable shelters that support decentralized disaster response

However, further research is required to validate the proposed system. Future studies should focus on (1) prototyping and full-scale fabrication, (2) real-world testing under disaster conditions, (3) structural and material performance evaluation, and (4) integration with disaster management systems, including logistics planning and emergency response protocols. Additionally, interdisciplinary approaches involving engineering, disaster management agencies, and local communities are necessary to ensure that portable shelter systems can be effectively implemented and scaled in real disaster scenarios.

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