Customising Emergency Shelter Design

Exploring spatial layout adaptability with AR-enhanced, LEGO-based design

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Addressing the challenges of environmental and urban crises requires rapidly deployable, adaptable emergency shelters. This study advances simplification, standardisation, and modularisation, shifting towards mass customisation in spatial planning out of five shelter design phases: emergency, temporality, transition, core unit design, and vertical expansion. We investigate the extent to which shelter layouts can be customised to meet diverse needs. Twelve participants designed custom layouts using LEGO-based models across two rounds, with an augmented reality (AR)-assisted interface developed to enhance the process. Findings highlight strengths and limitations of participant-generated designs, derived from sketches, and propose AR-driven optimisations to improve modularity, expandability, and adaptability. These insights enhance the potential of modular structures to address emergent shelter needs, offering practical solutions for dynamic crisis scenarios.
Keywords: *Spatial layout, Modular structures, Augmented Reality, Emergency shelters*

INTRODUCTION

Principles of variability, flexibility, and modularity provide more options and decisions for the end users of real-scale housing (Vahdati et al., 2024b). An immediate response to emergency relief with the potential of customization has not yet been explored for transitional/permanent applications. This paper tries to address them in terms of spatial planning. The research question the authors try to answer is, "To what extent can the spatial layout of the emergency shelters be customized?". This study is conducted to develop and explore different space planning alternatives using Augmented Reality (AR) as a design support. Design possibilities in linear and nonlinear modules could be discussed further for the spatial planning of emergency shelters using AR. Using AR technologies minimises materials, labour, infrastructure, and long-term environmental and energy costs (Vahdati et al., 2024a, e Gazel et al., 2018).

Emergency shelters can be categorised into five phases: (1) Temporary shelter, (2) Transitional shelters, upgradable shelters in terms of construction location or materiality, (3) Progressive shelters in terms of upgradable to permanent structures considering structural property and detailing, (4) Core shelters as the first part of permanent housing, (5) Permanent housing as reconstructed spaces for long term usage. The occupants may decide to turn these shelters into permanent homes, so their comfort and space should be increased. The other categorization of shelter types by IFRC (2013) is as follows (Karaoglan and Alaçam, 2018): (1) The emergency phase, (2) The temporary phase, (3) The transitional phase, (4) The core unit phase, (5) The vertical expansion phase. In this study, the emergency phase begins with physical spatial modelling using LEGO, followed by a transitional phase that investigates spatial expansion and adaptability through augmented reality (AR), with an emphasis on incremental values and upgradability over time. Incremental values are crucial for making the project viable by responding to family evolution and better economic scenarios. Incremental housing is a standard construction approach in developing nations. Homes are built with bare living essentials based on a family's financial capacity. As families grow or their economic circumstances improve, additional spaces can be incorporated into the shelter design, acknowledging that in certain contexts, these temporary shelters may evolve into long-term or permanent dwellings. While the current design system does not yet support this feature, the building system was developed to anticipate a future design framework where integrating incremental housing would be a sensible progression (Yao et al., 2023). In this paper, incremental shelters are discussed in more detail regarding the expandability of shelters in emergencies in the transitional phase.

Due to the immediate requirement for shelter, users cannot specify their preferences and needs. To address this, families could be classified according to their size, allowing for the creation of diverse configurations of modules (Karaoglan and Alaçam, 2018). With the increasing concern of disasters, emergency relief shelters' assembly and disassembly systems have become more discussed, especially regarding spatial arrangements.

METHODOLOGY

This study tests different layout configurations that could grow in complexity, size, and desired number of occupants by twelve participants with user participation in designing customized and user-co-designed architectural projects. The methodology in this paper is an experimental workflow tested in a workshop with twelve undergraduate architecture year 3 students. Ethical approval has been obtained for this data collection from Xian Jiaotong Liverpool University (XJTLU). The tools that are employed in this experiment are Input data (as collected data from students for designing their customized shelter), a set of LEGOs, Labels, a marker QR code, HoloLens 2 as an AR headset tool, Fologram for Rhino, and a Grasshopper file (Figure 1). The workflow process for the paper is as follows (Figure 2):

Figure 1
Materials provided for students in AR-assisted spatial planning with LEGOs: Input data, QR code marker, LEGOs, labels, questionnaire, and HoloLens 2

Phase 1) Categorization of the shelter types: to develop and explore different space planning alternatives, the users were asked to fill in the input data regarding the shelter types, number of people, desired floor area, number of spaces with the room functions, and room dimensions with design layout alternatives.

Phase 2) Development of an AR-assisted user interface considering the three criteria based on suitability for emergency shelter design: (1) construction without professional builders' help, (2) upgrading potential, (3) transformable elements for emergency shelters with design possibilities in linear and nonlinear modules.

Phase 3) Application of LEGO for the units and modules in different directions for the spatial layout of the emergency phase. This occurred in two main steps: (1) brainstorming and sketches (a minimum of about 3.5 square meters of covered living space per person is generally recommended for emergency shelters. Also, a Minimum of ~14 m² for four people (3.5 m² per person) is required in typical/improved design, often around 16–18 m² for a family of 4 to allow a slightly more comfortable arrangement), and (2) spatial arrangements with 13 types of LEGOs for the emergency phase (each one-by-one LEGO is considered as 1*1 square meter, and tags are used for the rooms such that they can be sorted).

Phase 4) Application of LEGO for the units and modules in different directions for the spatial layout of the transitional phase with extended spaces. This occurred in three main steps: (1) brainstorming and sketches, (2) spatial arrangements with 13 types of LEGOs for the transitional phase for the extensions, adding more rooms and spaces. Thus, the users try to move LEGO spaces to the grid and reassemble the planning with extra spaces added in different directions, considering the upgrade potential (transitional phase). What is essential in this section is the upgrade potential, the direction in which they will expand, and the connection they will start to expand using Augmented Reality (AR), and (3) AR-assisted design for the transitional shelter using HoloLens 2.

The users begin with the emergency phase and then go through the transitional phase using AR. Customized design with adaptable spaces is the primary concern that this phase tries to address.

Phase 5) The evaluation process was based on the user's feedback and the researcher's observation of the process (directly tracking the movements in the Rhino file).

During the experiment, time is recorded. The camera records the observation, and the pictures and videos are captured through the HoloLens 2 headset. The user's movement with the headset is tracked in a Rhino file on the laptop.

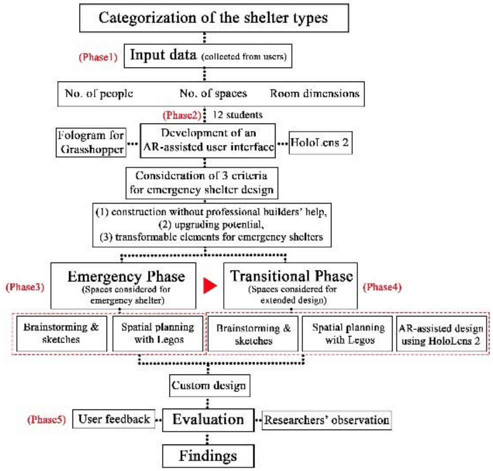

Figure 2
Methodology workflow diagram

VERIFICATION

The verification in this paper focuses on phases 03 and 04. The other phases have been tested in previous studies. The verification occurs during a workshop with 12 students operating in two groups. It starts with an introductory lecture and an introduction to HoloLens 2.

This study facilitates the development of an AR-assisted interface for a simplified LEGO-based model by addressing three key criteria relevant to emergency shelter design: (1) the ability to construct without professional assistance through a modular system that enables easy assembly and modification, (2) upgrade potential through the integration of additional design elements over time (e.g., extra LEGO modules), and (3) the inclusion of transformable components that support both linear and nonlinear spatial configurations, enabling multifunctional use of spaces, such as converting a sleeping area into storage.

FINDINGS

Augmented Reality (AR) integration in the spatial layout of emergency shelters

Applying digital technologies in post-disaster reconstruction is one of the aspects that is less discussed these days. Using AR technologies minimises materials, labour, infrastructure, and long-term environmental and energy costs.

In terms of interaction, AR can provide an immersive experience, allowing participants to interact with digital models of their designs. It also provides for real-time modifications, and participants can instantly see the implications of design changes, especially regarding disassembly and transport. Mixed reality environment could be discussed more in terms of scale, visualization, interactivity (using press, move, rotate, and scale), and display mode (rendered, shaded, wireframe, rendered wireframe, occluded wireframe, occluded silhouette, and rendered silhouette). The students found the rendered and shaded mode to visualise the model and massing more appropriately (Figure 3).

Figure 3
Model of the spatial planning made up of the digital LEGO in HoloLens 2

Most participants rated the spatial planning process using LEGO and HoloLens 2, including digital re-assembly, as highly effective (ratings 4–5 on a 5-point scale). On average, the physical assembly took 30 minutes, while the AR-based re-assembly required approximately 20 minutes. Air tap gestures were preferred over finger taps due to their greater interactivity.

The students' feedback shows that using the HoloLens 2 brought a new and engaging experience to their design process, especially since most had never used AR before. They found it both enjoyable and mentally stimulating. The ability to reconfigure designs and expand spatial layouts with digital LEGO-like elements helped some students better understand spatial relationships and sparked interest in exploring space creatively. One student highlighted how intuitive gestures like air-pinching and rotating made the interaction feel natural and easy. These features were seen as tools that could make architectural design more accessible in the future. Real-time visualization helped students better imagine and understand their ideas, and the user interface was described as interactive and fun. Overall, the use of HoloLens 2 supported creativity, exploration, and a deeper understanding of space in the design process.

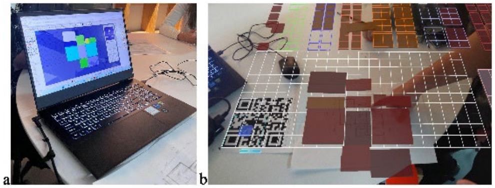

Figure 4
Their design on the paper was like a physical guide for them using AR.

The students suggested that digital elements within the HoloLens 2 environment should behave similarly to physical LEGO blocks—automatically connecting when brought into proximity, akin to magnetic attraction. This feature, they argued, would enhance the intuitiveness of the assembly process at a human scale. Additionally, they proposed that the system could provide real-time feedback or alerts when components are misaligned or structurally disconnected, particularly during disassembly, to simulate debris or instability warnings. Such enhancements would improve both the accuracy and safety-awareness aspects of spatial interaction in augmented reality.

The participants suggested that integrating an automated sensor for head-fitting would significantly enhance usability for beginners, allowing for quicker adjustments compared to the manual tightening mechanism at the back of the device. In terms of spatial guidance, the researchers provided a digital grid to assist students in determining the appropriate placement of their spatial configurations. Participants proposed that this grid would be more effective if it allowed the digital LEGO-like components to snap precisely into place, similar to magnetic attraction, thus facilitating alignment and coherence between adjacent spatial units. Furthermore, they recommended that the grid be dynamically linked to the model so that it could be repositioned collectively. The use of a physical marker on the table proved particularly beneficial in helping students anchor and position virtual spaces in the air. The scale interactivity feature was also positively received, as it enabled participants to customize spatial dimensions as needed (Figure 5).

Figure 5
a) Tracking user movements in the Rhino file, b)The grid with the digital LEGOs matching together

An important consideration for advancing AR-based design workflows involves enhancing the collaborative capabilities of devices such as the HoloLens 2. Specifically, improvements could focus on enabling simultaneous multi-user interaction, akin to Building Information Modeling (BIM) platforms, where multiple engineers or designers can access, modify, and visualize the same project in real-time. This functionality would be particularly beneficial in professional settings, allowing team members to co-design and respond to updates dynamically. In the current project, however, only one participant could engage with the AR environment at a time, while others were limited to observing and verbally guiding the active user. This often led to disengagement among team members, as illustrated in Figure 4, which captures this limitation in practice.

The experiment revealed key limitations in both traditional and AR-based design workflows. While the initial paper-based task was perceived by some participants as conventional and lacking engagement, the transition to AR with HoloLens 2 introduced its own challenges. Participants highlighted difficulties in achieving optimal visual alignment, the absence of a snap-to-place function, and limited visibility of digital components, which hindered precise spatial arrangement. The sequential use of the device further restricted collaboration, suggesting that current AR hardware may not yet fully support real-time group design interactions at scale. These findings underscore the need for enhanced usability and collaborative features in AR design tools.

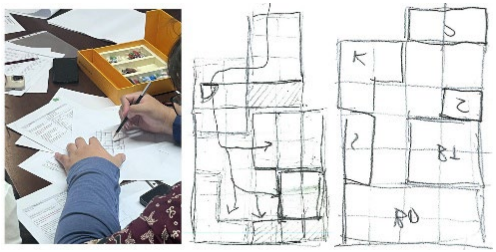

Figure 6
Considering circulation in the spatial layout

The participant's experience highlights the importance of usability and user comfort in AR environments. Although she initially faced difficulties adapting to the HoloLens 2 due to visual glitches and slight discomfort, continued use and proper guidance helped her overcome these challenges. Over time, the interaction became more intuitive and enjoyable, showing that while AR tools may present early learning barriers, they can become effective and rewarding with support and practice.

In this practice, the spaces that the participants in the group (a) considered in their design were the living room (2*3), dining room (3*3), bedroom (3*4), bathroom (2*1), laundry (2*1), kitchen (2*1), storage (1*1), porch (3*2), patio (2*1), garden (2*1), garage (3*2). Contextual and cultural aesthetics may also affect the size of their spaces. Participants tried to design their spatial layout non-linearly and had some fractures in the sides of the plan. The unit core they considered was the living room, and other spaces extended from the four directions of the core.

In their initial paper-based designs, participants demonstrated an awareness of circulation by planning spatial flow from entrance to exit—an essential consideration in emergency shelter design (Figure 6). They incorporated features such as stairs and prioritized spaces based on functional needs. When transitioning to the AR environment with digital LEGOs, students evaluated spatial relationships in sectional views, which became a key aspect of their design discussions and understanding of layout hierarchy.

In terms of participants' evaluations of using HoloLens 2 as an AR tool, The results show that students found the HoloLens 2 environment tracking and interface mostly user-friendly, but many faced challenges with movement tracing and interaction functions like move, rotate, and scale; opinions on material and colour quality were mixed, while the process of linking Fologram to the Rhino model was largely reported as easy and successful.

Participants' evaluation of the final design with LEGO using AR

Most students found LEGO materials in the experiment appropriate, noting the ease of attachment, clear connections, and overall visual satisfaction. However, two students expressed concerns about the scale of the LEGO pieces, suggesting that it limited modular flexibility within the design process. Additionally, five students indicated that the variety of LEGO types provided was insufficient to fully support the complexity and diversity of their design ideas.

The findings indicate that while most participants found the AR interface intuitive and enjoyable, significant usability challenges remain. Delays in system responsiveness affected the perceived efficiency for 40% of participants, and a notable portion found the experience physically (8 students) or mentally (5 students) demanding. Frustration with the interface was also reported by four students. Despite these limitations, 67% expressed a desire to use the interface in future design work, and half of the participants recognized AR's potential to enhance design freedom and customization. Most students agreed that rapidity, adaptability, and architectural quality are essential considerations for spatial arrangement in emergency shelter design, especially in disaster relief contexts.

Allowing for continuity in X, Y, and Z direction (Upgrade Potential), continuous and spacious in dimensions, and modularity (scale in dimensions X, Y, and Z) helps students in the transitional phase to expand the plan by responding to family evolution and better economic scenarios. The students found it quite relevant to their experience with AR. 75% of the students found the possibility of incremental and spontaneous design in their spatial planning for the emergency shelter design quite relevant. Unpredictability and diversity of cases are observed during their design when choosing the spaces and reassembling them in an AR environment.

Most students saw HoloLens 2 as a potential replacement for physical models due to its strong visualization capabilities. However, some preferred physical models for their tactile feedback, highlighting that AR's effectiveness depends on user familiarity and the need for sensory interaction in the design process.

One student noted that AR lacks the level of detail achievable through manual design and suggested improvements in features and graphics. Feedback on synchronizing elements from Grasshopper to HoloLens 2 via Fologram was mixed: five students found it challenging, five found it easy, and two reported it did not work. All students agreed that using LEGO was effective for early-stage design, as it is easy to assemble and disassemble, accurately represents dimensions, and supports quick, interactive spatial visualization.

The students' feedback highlights both the creative potential and usability challenges of the mixed reality environment. While many found the AR experience engaging and conducive to imagination throughout the design process, initial interactions were often overwhelming due to unfamiliarity with gesture-based controls and visual adjustments. Physical fatigue from hand gestures and the lack of precision in manipulating digital elements were cited as limitations. Suggestions for improvement included integrating snap functionality, enhancing material realism, and increasing the intuitiveness of object manipulation. Several students found the air tap physically tiring, and one highlighted the need for snap-to-place functionality to support precise assembly. Two students suggested improving the digital quality of materials and textures, while others viewed the re-assembly process in AR as an advancement over physical LEGO, praising its potential for speed and creativity if interaction precision is enhanced.

The feedback suggests that AR offers clear advantages in emergency shelter design, particularly for spatial zoning and rapid visualization, as noted by most students. However, its effectiveness is contingent on the user's familiarity with the technology. While some students acknowledged its potential to save time and improve spatial understanding in urgent contexts, concerns were raised about its accessibility for non-expert users in post-disaster scenarios. This highlights the need for user-friendly interfaces and targeted training to ensure AR can be effectively deployed in real-world emergency design applications.

Design sketches of emergency shelters

The workshop was conducted in two groups, each with six students, to observe how spatial configuration and group dynamics may influence collaborative design behaviour.

The first group was arranged for six people; they considered 4 square meters per person and designed for a family of five people, so they considered 20-40 square meters for their shelter design in emergency type. Table 1 reveals that while core functions like kitchen, bedroom, bathroom, and storage were consistently prioritized in emergency shelter layouts, extended designs commonly incorporated living and communal spaces, highlighting a shift toward flexibility, social needs, and spatial expansion in post-emergency scenarios (Figure 7).

Table 1
Consideration of spaces in the LEGO design of the participants (P) in the first group

P	Spaces for emergency shelter	Spaces for extended design
1	Kitchen and dining room(merged),bedroom, bathroom, storage	Livingroom
2	Kitchen and dining room (merged), bedroom, bathroom, storage	Living room, laundry room, porch, garden
3	Kitchen (1*2), bedroom, bathroom, storage (1*1)	Living room and dining room (merged, 3*3)
4	Kitchen, dining room, living room, bathroom, laundry room, stairway, storage, patio	Living room, patio
5	Kitchen (1*2) and dining room	living and dining room (merged, 3*3)

	(merged), bedroom, bathroom, storage	
6	Kitchen (1*2), bedroom, bathroom (1*2), storage (1*1) *She tried to solve the planning in a 4*8 grid, considering the potential of corners	Living room and dining room (merged, 3*3)

Figure 7 illustrates the emergency phase design using LEGO by the first group, followed by their group sketch and final design representing the transitional phase with extended spatial development.

The second group was arranged for a group of six people; they considered 4 square meters per person and designed for a family of four people, so they considered 20-40 square meters for their shelter design in a temporary type. Table 2 shows a consistent core layout across all emergency shelter plans, while extended designs emphasized spatial expansion through the addition of living rooms, garages, and enlarged or additional bedrooms and bathrooms, reflecting a focus on long-term adaptability and comfort. Figure 8 illustrates the initial sketch design for the emergency phase in the second group, followed by the final LEGO design for the transitional phase with an extended design. The LEGO sections also provide information regarding the priority of spaces in their design.

P	Spaces for emergency shelter	Spaces for extended design
1	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom, bathroom (extended), garage
2	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom, bathroom, garage
3	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom, bathroom(extended), garage
4	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom (+1), bathroom (extended), garage
5	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom (+1), bathroom (extended), garage
6	Kitchen, bedroom, bathroom, storage, porch	Living room, bedroom (+1), bathroom (extended), garage

Table 2
Consideration of spaces in the LEGO design of the participants (P) in the second group

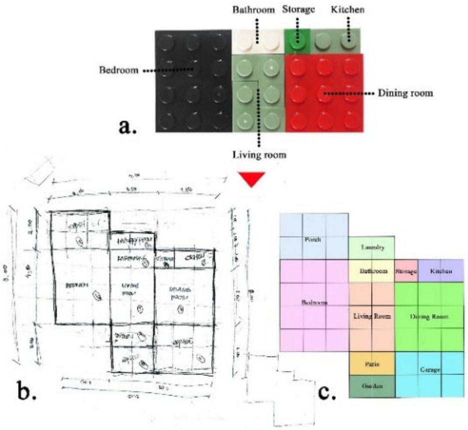

Figure 7
Emergency shelter design for the emergency phase (a), and the transitional phase for the extended spaces (b and c)

In both groups, the design for the emergency phase started with the linear modules but expanded to non-linear in a transitional phase. Most students found the Kitchen, bedroom, bathroom, storage, and porch as critical spaces in emergencies. Still, it can be extended in the transitional phase by a living room, laundry room, porch, garden, and garage for a family of four. The quality of design in the transitional phase is much more organized.

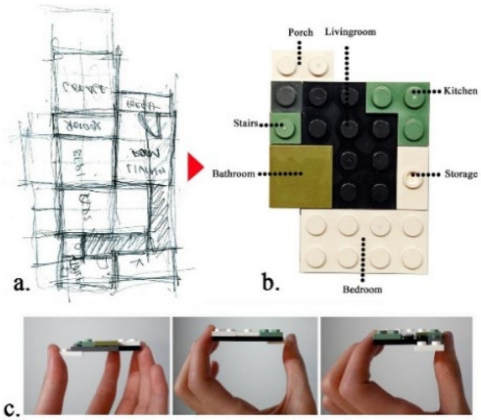

Figure 8
Emergency shelter design for a) the emergency phase, b) the transitional phase, c) the transitional phase, LEGO sections for the extended spaces

DISCUSSION AND CONCLUSIONS

This paper investigates the extent to which the spatial layout of emergency shelters can be customized. To explore this, the study simulates and analyzes shelter layouts using LEGO blocks, provided to twelve participants across two design rounds. The process addresses two key phases: the emergency phase and the transitional phase, the latter involving incremental spatial expansion over time. All design activities were recorded and assessed using an AR headset, which participants found intuitive to use. Feedback also emphasized the importance of labelling spaces in both physical and digital formats for clarity and usability. During the design, key findings were observed during the use of AR in the design process:

- Easier customisation and design freedom
- User familiarity and sensory needs in design
- Spatial zoning and rapid visualization
- Enhance speed and spatial clarity in emergencies
- Intuitive gestures like pinching, rotating, and assembling

Some limitations or challenges were also encountered in this experiment:

- The limited variety of LEGO types
- Unfamiliarity with gesture-based controls and visual adjustments
- Access for non-experts in post-disaster use

These insights have the potential to inform the development of future workflows and design tools:

- The system could give real-time alerts for misalignment or instability during disassembly
- Need for snap-to-place for precise assembly
- Enhancing digital material and texture quality
- Need for intuitive interfaces and focused training
- Safety-aware spatial interaction in AR
- Enhancing HoloLens 2 for simultaneous multi-user collaboration
- Auto-adjusting head-fit sensor

The modularity can be enhanced through:

- LEGO: easy assembly, clear connections, visual appeal, and ideal for early-stage design
- The possibility of incremental and spontaneous design
- Grid to aid alignment and spatial coherence
- Considering circulation in the spatial layout
- Sectional views for spatial relations and layout hierarchy
- Potential for speed and creativity with improved interaction precision

The identified weaknesses in this research could be discussed in several points:

- The scale of the LEGO pieces
- Delays in UI experience
- AR offers fewer design details than manual methods

- Variability and unpredictability in reassembly scenarios
- Favoured physical models for tactile engagement
- Auto-connecting when in proximity
- Occasional visual glitches causing potential discomfort

This paper explores AR-driven customization in disaster relief construction, simulating the adaptive growth of emergency shelters. While users can't always express preferences during crises, AR enables rapid, efficient, and flexible design tailored to future personalization. Future research will examine the cost implications of applying Design for Disassembly (DfD) in emergency shelter design. Key cost factors include material storage, labour and insurance, debris transport, hazardous material removal, training, market conditions, material quality, and landfill fees.

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