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Citation (APA)
Tak, M. D., & Akay, M. (2026). Parametric modelling for temporary housing areas: Integrating multi-source standards with multi-objective optimisation. *Progress in Disaster Science*, *29*, Article 100519.
https://doi.org/10.1016/j.pdisas.2026.100519

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Progress in Disaster Science 29 (2026) 100519

Contents lists available at ScienceDirect

Progress in Disaster Science

journal homepage: www.elsevier.com/locate/pdisas

Regular Article

Parametric modelling for temporary housing areas: Integrating multi-source standards with multi-objective optimisation☆

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ARTICLE INFO

Keywords:
Algorithmic design
Parametric modelling
Multi-objective optimisation
UNHCR
SPHERE
Temporary housing

ABSTRACT

Post-disaster planning demands swift yet quality-conscious decision-making under extreme time pressure and cognitive load, conditions under which conventional approaches frequently fail. While extensive research addresses site selection through multi-criteria decision analysis and GIS-based methods, a critical gap persists in the computational generation of internal site layouts that algorithmically integrate humanitarian spatial standards from multiple institutional sources. This study develops a generative design framework integrating parametric modelling with multi-objective evolutionary optimisation to address this gap. It translates qualitative standards from the SPHERE Association, UNHCR, and national guidelines into quantitative design parameters for temporary housing areas. The methodology proceeds in three stages: (1) systematic extraction and synthesis of spatial parameters from international (SPHERE, UNHCR) and national (AFAD, Chamber of Urban Planners) sources; (2) parametric modelling in Rhino-Grasshopper® to encode design parameters; (3) multi-objective optimisation using NSGA-II genetic algorithms to balance shelter capacity maximisation and 500-m pedestrian accessibility to service hubs. Applied to Ümraniye National Garden, a pre-designated 15-ha temporary housing site in Istanbul, the framework generated 2500 design alternatives, identifying 50 Pareto-optimal configurations spanning capacity-accessibility trade-offs from high-density solutions (1737 units, 19% accessible within 500 m) to accessibility-optimised layouts (1222 units, 92% accessible). This research contributes a replicable, standards-informed computational workflow that systematically reconciles multi-source humanitarian standards and generates site layouts through multi-objective optimisation, advancing beyond component-level optimisation and evaluation-focused approaches. By providing decision-makers with diverse Pareto-optimal alternatives rather than single predetermined solutions, the framework shifts temporary housing design from static manual drafting toward agile, evidence-based generative processes suitable for crisis decision-making contexts.

1. Introduction

Cities function as complex, interconnected systems. When sudden stressors such as disasters disrupt these systems, predictable dynamics rapidly shift into unpredictable configurations, transforming routine challenges into complex system problems requiring adaptive responses [1]. The linear nature of conventional planning approaches often fails to address these dynamic shifts effectively. Recent disasters, including the 2010 Haiti earthquake, the 2011 Tōhoku earthquake, and the 2023 earthquakes affecting Türkiye and Syria, have displaced millions, with some events requiring shelter provision equivalent to the population of entire cities within days. In such high-pressure contexts, the limited operational capacity of regular decision-making processes can lead to data misinterpretation and superficial shelter designs [2], directly threatening long-term inhabitant well-being as evidenced in temporary housing areas after major disasters [3,4]. Given the scale and urgency of such responses [5] oth the speed of deployment and the spatial quality of recovery environments are essential for affected populations' well-being.

Various digital methods have been developed to support post-disaster decision-making and mitigate cognitive load under time-constrained conditions. Existing approaches predominantly address site selection through multi-criteria decision analysis (MCDA) methods, including AHP, TOPSIS, and GIS-based suitability mapping [6], which have proven effective in identifying appropriate locations for temporary

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☆ This article is part of a Special issue entitled: 'Disaster and Shelter Management' published in Progress in Disaster Science.

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https://doi.org/10.1016/j.pdisas.2026.100519
Received 28 March 2025; Received in revised form 7 January 2026; Accepted 9 January 2026
Available online 10 January 2026
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housing. Recent work has extended computational design to humanitarian contexts at different scales. At the unit scale, studies have addressed shelter design through parametric optimisation [7] and digital fabrication methods [8,9]. At the site scale, several studies have explored algorithmic approaches to camp planning. Daher et al. [10] developed a parametric participative framework for spatial camp planning that incorporated stakeholder input. Andriasyan et al. [11] created an algorithmic planning framework for refugee camps that automated plot generation, optimised WASH (Water, Sanitation, and Hygiene) facility placement using genetic algorithms, and analysed fire safety through graph traversal methods. More recently, Lima et al. [12] applied generative design to enhance transit accessibility and walkability in urban contexts, demonstrating the potential of computational approaches to address mobility-related quality of life factors.

While these contributions advance the field, three interconnected gaps persist in the computational design of temporary housing areas. First, existing work on internal site layout generation remains limited compared to the well-developed body of site selection methodologies. Studies such as Andriasyan et al. [11] demonstrate component-level optimisation for specific facilities within assumed spatial frameworks, but do not address the holistic generation of complete site configurations that integrate road networks, service distributions, and shelter clusters simultaneously. Second, although multiple humanitarian frameworks provide spatial guidelines for temporary housing, these standards often diverge on critical parameters such as road widths, service area distances, and facility hierarchies. No systematic method exists to extract, compare, and computationally operationalise these conflicting qualitative guidelines into coherent quantitative design parameters. Existing approaches either assume predefined standards without justification or focus on single frameworks, leaving the challenge of reconciling multiple sources unaddressed. Third, conventional computational approaches typically optimise specific components or generate single design solutions, failing to explore trade-off spaces across competing objectives at the site scale. While Andriasyan et al. [11] applied multi-objective optimisation to facility placement, the broader question of how to balance shelter capacity against accessibility, or other critical humanitarian dimensions, across an entire site layout remains unexplored. These gaps are particularly critical in seismically active regions where pre-designated sites require rapid yet standards-compliant internal layout design.

Among regions facing acute seismic risk, Türkiye presents a critical context for advancing temporary housing design methodologies. The country's location on active tectonic boundaries has resulted in recurring displacement crises. The 23 October 2011 Van-Erciş earthquake displaced 35,000 people, requiring 35 container cities by early 2012 [13]. The scale of displacement intensified dramatically following the 6 February 2023 Kahramanmaraş earthquakes, which affected 11 provinces and displaced 1.55 million people, necessitating 345 tent cities and 305 container cities [13]. Currently, for the anticipated Marmara earthquake with an estimated magnitude of 7.2, projections indicate approximately 3 million people will require housing in Istanbul alone [14]. Many potential temporary housing locations have been pre-designated through municipal disaster preparedness plans, yet the design of their internal layouts continues to rely heavily on manual drafting processes that cannot systematically integrate conflicting standards or explore design trade-offs under time pressure. Motivated by this urgent context and the identified research gaps, this study addresses the question: How can international and national humanitarian spatial standards be computationally operationalised to generate optimised temporary housing layouts that balance shelter capacity with accessibility under post-disaster time constraints?

From this critical perspective, this study proposes a generative design framework that systematically translates humanitarian spatial standards into algorithmic parameters for multi-objective optimisation of temporary housing layouts. The framework consists of three stages: (1) extracting and synthesising spatial parameters from international (SPHERE, UNHCR) and national (AFAD, Chamber of Urban Planners) sources, identifying convergences and conflicts across frameworks; (2) parametric modelling in Rhino-Grasshopper® to algorithmically encode design constraints such as road networks, firebreaks, setbacks, and service distributions as design rules; (3) multi-objective optimization using evolutionary algorithms (NSGA-II) to balance shelter capacity maximisation with pedestrian accessibility to essential services, generating Pareto-optimal solution sets. To demonstrate practical applicability, the framework was applied to Ümraniye National Garden, a pre-designated temporary housing site in Istanbul measuring approximately 15 ha, generating design alternatives with Pareto-optimal configurations.

By doing so, this research contributes a replicable methodological framework for converting standards into quantitative generative design parameters, addressing the lack of systematic translation mechanisms between policy documents and spatial planning tools. Through its adaptive algorithmic workflow, the study demonstrates how computational design can generate thousands of optimised layout alternatives rather than single predetermined solutions, enabling decision-makers to explore trade-offs between competing objectives under crisis conditions. The empirical application provides evidence that algorithmic approaches can support spatial planning within operationally relevant timeframes, producing viable solutions that achieve up to 1231 housing units with 92% accessibility to essential services within 500 m. Through this approach, the study contributes to the rapid generation of alternatives, evidence-based decision-making for Istanbul and other seismically active urban regions, with the potential to improve post-disaster recovery by enhancing the spatial quality of life in temporary housing environments.

The remainder of this paper is organised as follows. The next section reviews computational design approaches in disaster management and humanitarian spatial standards. The methodology section then details the standard extraction process, parametric modelling workflow, and multi-objective optimisation procedure. Results present the generated design alternatives and their performance metrics. The discussion contextualises findings within existing literature, addresses limitations, and identifies implementation considerations. Finally, the conclusion synthesises key contributions and outlines directions for future research.

2. Literature review

2.1. Decision support tools in disaster management

While managing urban complexity is already challenging under normal conditions, producing effective solutions becomes even more difficult when cities are faced with sudden shocks such as disasters. The dynamic nature of cities exceeds the cognitive and institutional capacity of individual decision-makers to fully grasp processes, anticipate all possibilities, or keep pace with urban change [15]. For this reason, various decision support tools have been developed to assist planning actors across the stages of urban planning.

The utilisation of decision support tools at different phases of the planning process is frequently emphasised in the literature, particularly in disaster-focused issues. Existing research agenda addresses a wide range of applications, including the identification of risk-prone areas before disasters [16], site selection for post-disaster shelter areas [17], and the simulation of disaster scenarios through approaches such as agent-based modelling [18]. These tools are primarily employed to manage and mitigate disaster impacts across different temporal and spatial scales.

Beyond analytical and predictive tasks, however, the site selection and design of shelter areas constitute critical components of post-disaster recovery, as they directly influence the ability of affected communities to return to everyday life. Due to the urgency of decision-making in post-disaster contexts, shelter design processes are often reduced to rapid and superficial solutions, which may threaten the long-term health and well-being of residents. For instance, following

Hurricane Katrina, elevated levels of volatile chemicals were detected in temporary housing units as a result of inadequate ventilation and material choices ([19], as cited in [6]). Similarly, after the 2011 Tōhoku earthquake, the term kodokushi emerged to describe deaths associated with social isolation and poor living conditions in temporary housing areas, revealing the social consequences of low-quality post-disaster environments ([3,4], as cited in [6]).

In response to the challenges posed by rapid post-disaster decision-making, a wide range of decision support systems has been developed alongside advances in computational technologies, particularly for land allocation and disaster management. Perrucci and Baroud [6] systematically reviewed temporary housing studies published between 2007 and 2020, identifying a diverse methodological landscape that can be broadly categorised into three groups. First, evaluation and assessment methods such as cost–benefit analysis [20] and social life cycle assessment (S-LCA) [21] are employed to quantify the economic, environmental, and social performance of shelter alternatives. Second, multi-criteria decision-making techniques, including the Analytical Hierarchy Process (AHP) and TOPSIS [22], enable the ranking of predefined options based on weighted criteria such as proximity to services, construction cost, or stakeholder preferences. Third, optimisation approaches, including multi-objective optimisation [23], genetic algorithms [24], and heuristic methods [25], are applied to identify optimal configurations within predefined design spaces, typically for site selection or resource allocation problems. Despite their methodological sophistication, these approaches share a common characteristic: they are predominantly applied to evaluate, rank, or select among predefined alternatives, rather than to generate diverse spatial configurations or explore design solution spaces. The distinction between optimisation of given alternatives and generation of novel design possibilities represents a critical methodological gap in the field.

The limitations of evaluation-focused methods have motivated interest in computational design approaches that can generate, rather than merely assess, spatial alternatives. Computational design enables the algorithmic encoding of design constraints and objectives, allowing rapid exploration of large solution spaces through parametric modelling and optimisation [26]. This generative capacity is particularly valuable in humanitarian contexts where time is a defining constraint [11], yet systematic integration of computational design with post-disaster shelter planning remains limited and unevenly developed across different design scales and objectives.

2.2. Computational design as a response tool

Computational design offers a complementary approach to the evaluation-focused methods discussed above by enabling the algorithmic generation and exploration of design alternatives [27]. Rather than assessing predefined options, computational design encodes spatial rules, constraints, and objectives into generative algorithms that can produce and evaluate thousands of potential configurations within short timeframes [28]. This capacity for rapid design space exploration is particularly valuable in post-disaster contexts where decision-makers face severe time pressure yet require solutions that balance multiple competing objectives. By parameterising design variables and embedding domain-specific constraints, computational approaches can systematically explore trade-offs between shelter capacity, accessibility, safety, and other humanitarian priorities while maintaining compliance with established standards.

Recent work has begun to apply computational design methods to humanitarian shelter planning across multiple scales. At the unit scale, researchers have developed parametric approaches for individual shelter design [8], optimised shelter configurations using soft computing techniques [7], and generated latrine unit designs through algorithmic methods [9]. At the site scale, several studies have explored computational frameworks for camp planning. Daher et al. [10] and Daher and Kubicki [29] developed a parametric participative framework for spatial camp planning that incorporated stakeholder input into the design process. Andriasyan et al. [11] created a more comprehensive algorithmic planning system for refugee camps that automated plot generation based on UNHCR standards, applied genetic optimisation to WASH facility placement to minimise service distances and infrastructure costs, and implemented graph traversal algorithms to analyse fire propagation risks. At the urban scale, Lima et al. [12] demonstrated how generative design can optimise transit accessibility and walkability, producing layout alternatives that reduce vehicle dependence. While these contributions demonstrate the potential of computational design to address specific components of humanitarian planning, several limitations persist. Existing studies typically focus on optimising individual facility types or subsystems within assumed spatial frameworks rather than generating holistic site configurations. More critically, no systematic method has been developed to extract and reconcile conflicting spatial standards from multiple humanitarian frameworks and translate them into coherent computational parameters. Andriasyan et al. [11], for instance, automated plot generation based on predefined UNHCR standards, but did not address how to computationally reconcile divergences between different standard-setting organisations, nor did their optimisation extend to complete site layout generation that integrates road networks, service distributions, and shelter clusters simultaneously. The gap between component-level optimisation and standards-informed holistic site generation remains unaddressed in the literature.

For post-disaster temporary housing layout generation, this study integrates parametric modelling with multi-objective optimisation – a hybrid approach that combines the constraint – encoding capacity of parametric systems with the solution-exploration power of evolutionary algorithms. This integration is particularly suited to the research problem because it allows humanitarian spatial standards to be systematically translated into algorithmic constraints (parametric component) while simultaneously exploring trade-offs between competing objectives such as shelter capacity and accessibility (optimisation component). The algorithmic framework provides transparency and adaptability, enabling rapid reconfiguration when different standard sets or site conditions are encountered, while the optimisation process generates diverse solutions rather than single predetermined layouts.

2.3. Standards for shelter/temporary housing areas

Standards serve as critical instruments for translating broad humanitarian goals into actionable design decisions. By establishing clear quantitative boundaries, standards reduce decision-making time and support rapid yet defensible planning in highly complex post-disaster contexts [30]. Multiple organisations have developed spatial standards to guide temporary housing design, though these frameworks often emerge from different mandates, contexts, and priorities, leading to divergences in specific parameters.

At the international level, two frameworks dominate humanitarian shelter planning. The SPHERE Project, initiated in 1997 by numerous non-governmental organisations, the Red Cross, and the Red Crescent, published its handbook in 2018, a 458-page resource outlining standards across humanitarian aid principles, water supply, sanitation, hygiene, food security, and shelter and settlement [31]. The UNHCR Handbook for Emergencies, released in 2007, provides a 595-page guide oriented primarily toward refugee contexts, covering emergency management, operations, spatial standards, logistics, health, and hygiene [32].

At the national level, Türkiye has established its own regulatory framework. The 2015 Directive on Temporary Accommodation Centres [33] legally defines spatial standards for post-disaster settlements and refugee camps within Turkish jurisdictions. Following the devastating 6 February 2023 Kahramanmaraş earthquakes, which claimed 50,783 lives and caused economic losses of 2 trillion Turkish Lira [34,35], the Chamber of Urban Planners (CUP) of Türkiye (2023) published an updated guide synthesising international standards with context-specific requirements for earthquake-prone regions. These national sources provide more prescriptive guidance on certain parameters such as road widths and entrance dimensions, reflecting Türkiye's institutional capacity for detailed planning as well as lessons learned from recent disaster experiences.

To identify patterns across these frameworks, a systematic comparison of spatial parameters was conducted through a detailed manual review of the SPHERE handbook's “Shelter and Settlement” section, the UNHCR handbook's “Site Selection, Planning, and Shelter” section, AFAD's directive, and the CUP's guide. Table 1 summarises the extracted spatial standards organised by category: site selection criteria, settlement unit specifications, safety requirements, and facility provisions.

Several patterns emerge from this comparative analysis. First, a consensus exists on fundamental safety parameters. All four sources prescribe 30-m firebreaks at 300-m intervals and specify a minimum 3-m elevation above water levels during site selection. Second, divergence appears in operational details. While SPHERE and UNHCR recommend 2-m lateral setbacks between shelter units, AFAD prescribes 5 m from roads, and the CUP differentiates between 2-m inter-unit spacing and 6-m cluster separation. Similarly, road widths are specified only by national sources (AFAD: 10–15 m; CUP: 6–10-15 m), suggesting that international frameworks delegate such context-dependent decisions to local authorities. Third, hierarchical structures differ. UNHCR establishes a detailed population-based hierarchy (16 families per community, 16 communities per block, 4 blocks per sector, 20,000 people per camp module with a minimum of 9 ha), while national sources use simpler structures (CUP: 16 families per community, maximum 2500 people per neighbourhood). Fourth, facility standards show the greatest variation. UNHCR and SPHERE define facility requirements per population thresholds (e.g., health area per 10,000 people), whereas AFAD specifies absolute minimum areas (health: 3000 m^2, education: 1500 m^2), and only the CUP establishes a maximum 500-m walking distance to service centres.

These divergences reflect genuine tensions in humanitarian planning. International frameworks prioritise flexibility and adaptability across diverse contexts, deliberately leaving certain parameters unspecified to accommodate local conditions and institutional capacities. National frameworks, operating within specific regulatory environments and drawing from experiential learning, tend toward more prescriptive guidance that can accelerate decision-making but may reduce adaptability. The critical challenge for computational design lies not in selecting one framework over others, but in systematically coupling these differences to produce coherent spatial configurations.

This study addresses these concerns by encoding standards as adjustable parameters within a generative framework, allowing decision-makers to prioritise specific frameworks or create hybrid rule sets appropriate to their context. The parametric model developed here uses AFAD's container dimensions (3 × 7 meters), the CUP's 500-m accessibility threshold, UNHCR's firebreak intervals, and synthesises setback requirements across sources. This approach transforms conflicting standards from barriers into design variables, enabling systematic exploration of how different rule combinations affect spatial outcomes such as shelter capacity and service accessibility.

3. Methodology

3.1. Case study selection and scope definition

Türkiye's active tectonic setting has historically resulted in large-scale displacement requiring extensive temporary housing infrastructure. Recent events present the magnitude of this challenge: the 2011 Van earthquake necessitated 35 container cities accommodating 175,000 people, while the 2023 Kahramanmaraş earthquakes displaced 1.55 million individuals across 650 temporary settlements [13]. For the anticipated Marmara earthquake (estimated magnitude 7.2), projections indicate approximately 3 million people will require housing in Istanbul alone [14]. In preparation for this scenario, municipal authorities have pre-designated sites for temporary housing, including Ümraniye

Table 1
Standards defined by the sources.

		UNHCR	SPHERE	AFAD	CUP
Location selection	ground slope	2%–4%	max 5%	4–2% max 7%	2–6%
	distance from the water level	min 3 m above	min 3 m above	min 3 m above	min 3 m above
	soil conditions	good for water emission		good for water emission	good for water emission
Standards for settlement units	required minimum area per person	45 m^2–30 m^2 (plots included)	45 m^2–30 m^2 (plots included)		45 m^2
	living space / covered space	3.5–4.5 m^2	3.5 m^2–5.5 m^2		3.5 m^2
	family size	4–6 people			3 people
	community	16 families			16 families
	block	16 communities			
	sector	4 blocks			
	camp module	20,000 people (min 9 ha)			
	neighbourhood			max 2500 person	16 communities
	tent/container sizes	3*6 = 18 m^2		3*7 = 21 m^2 container 4*4 = 16 m^2 tent	
Firebreaks		30 m for every 300 m	30 m for every 300 m	30 m for every 300 m	30 m for every 300 m
Setbacks		5–7 from roads	2 m for every house unit	5 m from the road, 2 m from the sides	2 m from sides / 6 m from every cluster
Facilities	latrine	1 per family/max 20 people	1 per family / 5 people		1 per community
	sanitation				1 per community
	health area	1 per camp module	per 10,000 people	min 3000 m^2	for facilities, 45 m^2 per person in total
	education area	1 per sector		min 1500 m^2	
	garbage	1 per community			2 per community
	market	1 per camp module		min 4000 m^2	
	socio cultural area	1 per camp module		min 500 m^2	for facilities, 45 m^2 per person in total
	distribution point	4 per camp module			
	feeding centre	1 per camp module			
	entrance door			8 m width	15 m width
	roads			15–10 m width	6–10-15 m width
	walking distance				max 500 m to the centre

National Garden, a 15-ha area in Istanbul selected as the case study for this research (Fig. 1).

The decision to focus on internal site layout design rather than site selection reflects both a strategic research focus and an identified literature gap. While site selection methodologies have been extensively developed using multi-criteria decision analysis, GIS-based suitability mapping, and optimisation techniques [6], the subsequent stage of generating optimised internal spatial configurations within pre-selected sites remains underdeveloped. In practice, many temporary housing locations are predetermined through municipal disaster preparedness plans, as in Istanbul's case, yet the design of their internal layouts still relies heavily on manual drafting. By concentrating on this overlooked phase, this study addresses a practical bottleneck in disaster response workflows while contributing a complementary tool to existing site selection frameworks. The Ümraniye National Garden site provides an operationally relevant context for testing the generative design framework, as it represents a realistic scenario where site boundaries are given, and the challenge lies in rapidly generating standards-compliant internal configurations.

The Ümraniye National Garden currently functions as a public recreational area, containing sports facilities, walking and cycling routes, vehicular roads, and scattered vegetation, including trees and partially sloping topography. While the site's current characteristics, including slope variation and distance from the urban core, might not satisfy all ideal site selection criteria discussed in humanitarian guidelines, it was officially designated as a temporary housing zone by Istanbul municipal authorities, reflecting the reality that site availability in densely populated urban areas often involves trade-offs between ideal conditions and practical constraints (Pezzica et al., [36]).

Several modelling assumptions were made to maintain focus on the core research contribution while acknowledging their implications. First, the parametric model operates on site boundaries as primary input, abstracting existing vegetation, topography, and current land uses. This simplification is justified on three grounds: (1) standard practice in temporary housing deployment involves site clearance and levelling operations before shelter installation [32,33], making the assumption of prepared ground operationally realistic; (2) the generative framework is designed as a flexible tool capable of adapting to varying site geometries, meaning that if specific areas must be excluded due to steep slopes, dense vegetation, or other constraints, users can adjust input boundaries accordingly during application; (3) the research priority is demonstrating systematic standards reconciliation and multi-objective layout optimization, capabilities that remain valid regardless of site-specific topographic conditions. Second, the study models two primary objectives (shelter capacity and accessibility to services) rather than a comprehensive set of humanitarian dimensions such as social cohesion, community space allocation, or psychological well-being indicators. This limitation reflects both methodological constraints and research focus: operationalising subjective quality-of-life factors into quantitative optimisation objectives remains an open research challenge [37], and the selected objectives represent the most commonly prioritised and quantifiable trade-offs in humanitarian shelter planning [6]. Future extensions of the framework could incorporate additional objectives as operationalisation methods develop.

Site boundary data were obtained from OpenStreetMap, an open-source geospatial platform widely used in humanitarian response contexts for rapid mapping [5]. Design parameters were systematically derived from the standards comparison presented in Section 2.3, integrating specifications from SPHERE, UNHCR, AFAD, and the Chamber of Urban Planners. The algorithmic framework encodes these parameters as generative rules, producing alternative spatial configurations optimised according to defined objectives, as detailed in the following subsections.

3.2. Defined parameters and workflow of the design algorithm

The algorithmic framework developed in this study translates the spatial standards into a parametric model that generates optimised temporary housing layouts. The framework pursues two primary objectives: maximising shelter capacity to accommodate the largest possible displaced population within the available site, and maximising the proportion of shelters accessible within 500 m walking distance to essential service facilities. These objectives reflect the fundamental trade-off in humanitarian shelter planning between accommodation density and quality of life through service access. The 500-m threshold was adopted from the CUP's guidelines, which identify this distance as a reasonable maximum for daily walking trips to essential services such as health facilities, education, and markets, particularly for vulnerable

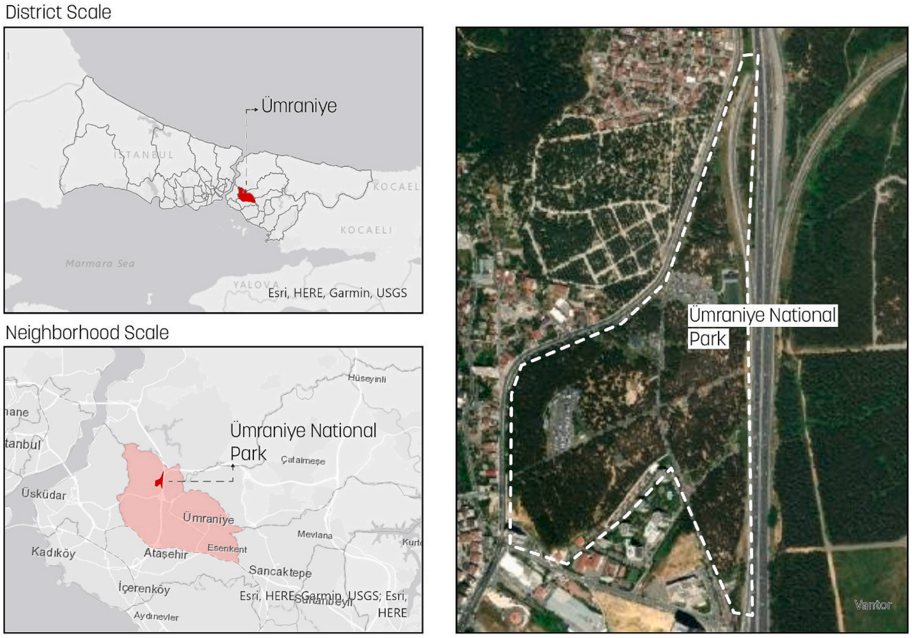

Fig. 1. Location of Ümraniye National Garden in Istanbul in different spatial scales, a pre-designated temporary housing site (15 ha), used as the case study for testing the generative design framework.

populations, including elderly residents, individuals with mobility limitations, and families with young children. While capacity maximisation addresses the immediate need to shelter displaced populations at scale, accessibility optimisation ensures that the resulting layouts support long-term habitability and community function rather than prioritising density alone.

The parametric model begins by encoding fundamental safety and regulatory constraints derived from converging international and national standards. An 8-m setback from the site boundary was applied following the CUP's specification, which mandates this buffer to separate shelter units from external roads and site perimeters, providing space for emergency vehicle access, utility infrastructure, and fire safety clearance. This parameter represents a synthesis of AFAD's 5-m road setback requirement and UNHCR's guidance on perimeter buffer zones. Firebreaks, prescribed universally across UNHCR, SPHERE, AFAD, and Chamber standards, were encoded as 30-m-wide cleared zones at 300-m intervals throughout the site. These firebreaks serve dual purposes: containing potential fire propagation between shelter clusters [11] and providing secondary circulation routes for emergency response vehicles. The algorithm identifies firebreak positions by systematically dividing the site into 300-m segments, with firebreak intersections at the site boundary serving as candidate locations for service facility placement in subsequent optimisation steps.

Internal road networks were configured at a 10-m width based on AFAD [33] and Chamber of Urban Planners (2023) specifications for primary circulation routes within temporary housing areas. This width accommodates two-way vehicle traffic for service delivery, waste collection, and emergency response while providing pedestrian walkways along road edges. The positioning of roads follows a grid-based logic structured around cluster dimensions. Shelter clusters, defined as groups of housing units sharing common sanitary facilities, were dimensioned using the following geometric relationship:

$$\textit{Block width} = (\mathrm{x} \times \text{shelter width}) + [(\mathrm{x}-1) \times 2] + \text{sanitary area width} + \text{lateral setbacks} \tag{1}$$

where x represents the number of shelter units per cluster (set to 8 units following the Chamber's recommended cluster size for community formation and service efficiency), shelter width is 7 m (AFAD's standard container dimension), the term $(\mathrm{x}-1) \times 2$ accounts for the 2-m lateral setbacks between adjacent units as specified by SPHERE and AFAD, sanitary area width is 6 m (minimum dimension for communal latrine and washing facilities per UNHCR standards), and lateral setbacks total 4 m (2 m on each side of the sanitary area). Applying these values yields a block width of approximately 80 m: $(8 \times 7) + (7 \times 2) + 6 + 4 = 80$ m). This calculation establishes the spacing interval for internal roads, which systematically subdivides the area between firebreaks and site boundaries into buildable blocks. Within each block, shelter units are positioned with 2-m lateral spacing (SPHERE, AFAD) and 5-m setback from roads (AFAD, UNHCR), balancing fire safety requirements with efficient land use. Units that overlap with roads or violate boundary constraints are automatically removed by the algorithm. To enable exploration of diverse spatial arrangements, the entire layout is subject to rotation between 0 and 90 degrees, a parameter that varies across optimisation iterations to test how building orientation affects capacity and accessibility outcomes.

Service facility placement represents a critical design decision with cascading effects on accessibility and internal circulation patterns. Rather than pre-specifying facility locations, the algorithm treats service area placement as an optimisation variable, positioning a 9000-square-meter service hub at one of the firebreak intersection points identified during the boundary constraint phase. The 9000-square-meter size was derived by aggregating minimum facility requirements specified by AFAD: 3000 m^2 for health services, 1500 m^2 for education facilities, 4000 m^2 for market and distribution areas, and 500 m^2 for socio-cultural spaces. This aggregation simplifies the model by treating essential services as a unified hub rather than distributing individual facilities, a design strategy that concentrates foot traffic, supports service synergies (e.g., combining health visits with market trips), and simplifies infrastructure provision (shared utilities, centralised waste management). However, this approach also introduces a potential accessibility limitation: residents distant from the hub face longer trips to all services. The hub's radial coverage assumption (services equally accessible from all directions within the service area boundary) represents a simplification that abstracts internal circulation within the facility zone, focusing computational resources on site-scale layout optimisation rather than facility-level planning.

Accessibility analysis operationalises the 500-m walking distance objective through network-based distance calculations. After shelter units and road networks are generated, the algorithm projects each unit's centroid to the nearest road centreline, establishing entry points to the pedestrian/vehicular network. Walking distances from each shelter to the service hub are then calculated using the A* pathfinding algorithm [38], a heuristic search method widely applied in spatial analysis for efficient shortest-path computation. The A* algorithm operates according to the following evaluation function:

$$F(n) = g(n) + h(n) \tag{2}$$

where $F(n)$ represents the total estimated cost from the start node to the goal through the node n, $g(n)$ is the actual path cost from the start node to the current node n, and $h(n)$ is the heuristic function estimating the remaining cost from node n to the goal. The algorithm iteratively selects nodes with the lowest $F(n)$ values, systematically expanding the search toward the goal while minimising unnecessary path exploration. This heuristic-guided approach was selected over alternative methods such as Dijkstra's algorithm or straight-line Euclidean distance for two reasons: first, it accounts for actual network paths rather than unrealistic straight-line distances; second, its heuristic function reduces computational overhead compared to exhaustive search methods like Dijkstra, enabling faster evaluation of thousands of design alternatives during optimisation. The algorithm is implemented through the Shortest Walk GH plugin in Grasshopper®, which constructs a graph representation of the road network and computes shortest paths between shelter nodes and the service hub node. For each generated layout, the algorithm counts the number of shelters accessible within 500 m, providing the accessibility objective value used in multi-objective optimisation described in Section 3.3.

Fig. 2 illustrates the complete algorithmic workflow, showing how standards-derived parameters flow through geometric operations (boundary setbacks, firebreak placement, road grid generation, cluster positioning) to produce candidate layouts, which are then evaluated for capacity (shelter unit count) and accessibility (proportion of units within 500 m of services). This generative process, iterated across varying parameter combinations and rotation angles during optimisation, systematically explores the design space defined by standards by producing a diverse set of layout alternatives.

3.3. Multi-objective optimisation of the algorithm

The parametric framework described in Section 3.2 generates spatial layouts based on encoded humanitarian standards, but the large solution space created by variable parameters (firebreak positions, road placements, rotation angles, service hub locations) contains thousands of possible configurations with varying performance across competing objectives. Selecting an appropriate layout from this space requires systematic evaluation and comparison, a task that exceeds human cognitive capacity under post-disaster time constraints when decision-makers must rapidly assess trade-offs between shelter capacity and accessibility. To address this challenge, this study employs multi-objective evolutionary optimisation [39] to automatically explore the

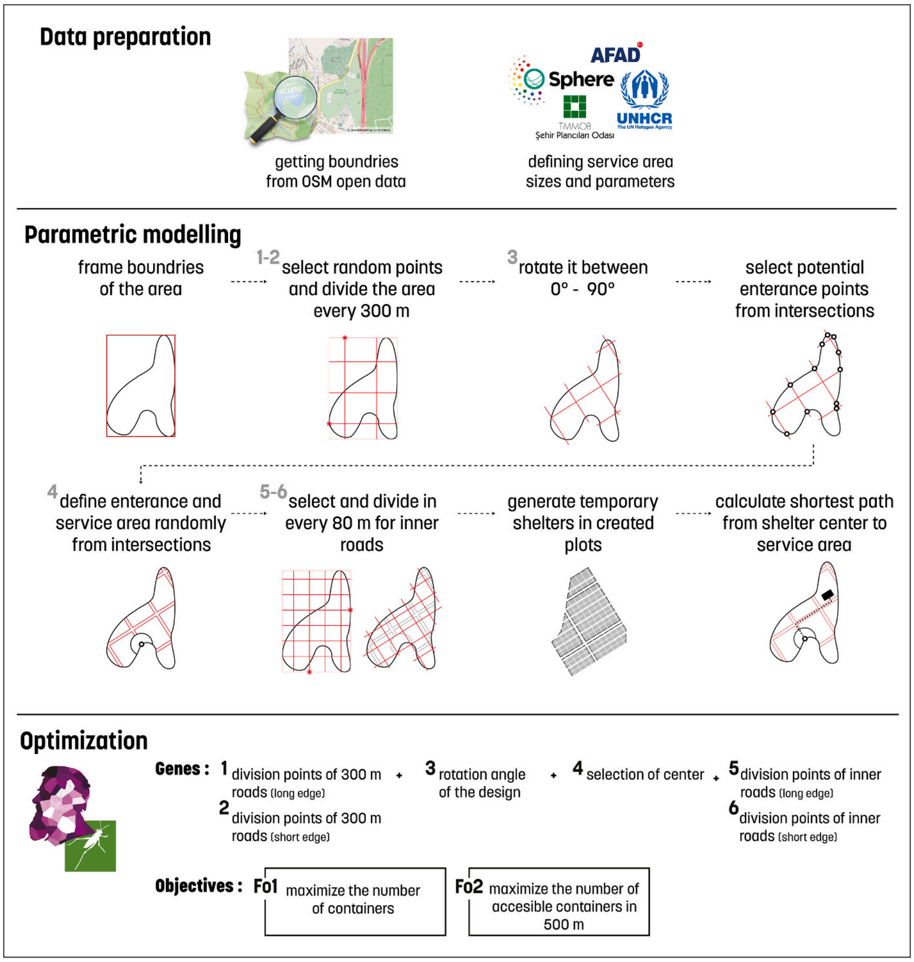

Fig. 2. General steps of the research framework, including data preparation, parametric modelling and optimisation stages.

design space and identify a set of high-performing solutions that represent optimal trade-offs between objectives, rather than attempting to find a single *best* solution that may not exist when objectives conflict.

Multi-objective optimisation was selected over single-objective approaches (such as weighted aggregation of capacity and accessibility into a single metric) for two methodological reasons. First, humanitarian decision-making contexts involve stakeholders with diverse priorities: municipal authorities may prioritise capacity to meet political commitments for sheltering specific population targets, while humanitarian organisations may emphasise accessibility to ensure quality of life standards, and community representatives may advocate for social cohesion factors. Pre-defining relative weights for these objectives (e.g., “capacity is twice as important as accessibility”) would impose researcher assumptions onto a fundamentally context-dependent and stakeholder-negotiated decision process. Second, Pareto-based multi-objective optimisation generates a set of non-dominated solutions [40], where improving one objective necessarily requires degrading another, thereby revealing the inherent trade-off structure of the problem and empowering decision-makers to select solutions aligned with their context-specific priorities rather than accepting a single pre-optimised outcome [41].

The optimisation was executed using the Wallacei Analytics® and Wallacei X® [42], a Grasshopper® plugin specifically designed for architectural and urban design optimisation problems. Wallacei Analytics® employs the NSGA-II (Non-dominated Sorting Genetic Algorithm II) evolutionary algorithm, a widely adopted multi-objective optimisation method that maintains population diversity through non-dominated sorting and crowding distance mechanisms, preventing premature convergence to local optima and ensuring broad coverage of the Pareto Front. NSGA-II operates through an evolutionary process analogous to natural selection: a population of candidate solutions (layout configurations) is iteratively evaluated, with high-performing individuals (layouts achieving superior capacity and accessibility) selected for reproduction (generating new variations through crossover and mutation operations), while poorly performing solutions are eliminated. Over successive generations, the population evolves toward the Pareto Front, identifying layouts where no objective can be improved without degrading another.

Within the scope of this study, two fitness objectives guide the optimisation process. Fitness Objective 1 (Fo1) maximises the total number of shelter units accommodated within the site boundaries, representing the capacity objective that addresses the immediate need to shelter displaced populations at scale. Fitness Objective 2 (Fo2) maximises the number of shelter units accessible within 500 m walking distance to the central service hub, representing the accessibility objective that ensures long-term habitability and quality of life through reasonable access to essential services such as health facilities, education, and markets. The Pareto Front captures this duality, presenting a spectrum of solutions ranging from high-capacity/lower-accessibility layouts to lower-capacity/high-accessibility configurations.

Decision parameters represent the parameters manipulated by the optimisation algorithm to generate different layouts. Four parameters were defined as follows: (1) firebreak division line positions (selecting among possible 300-m interval configurations within the site), (2) internal road division lines (selecting among possible 80-m grid configurations), (3) overall layout rotation angle (continuous variable ranging

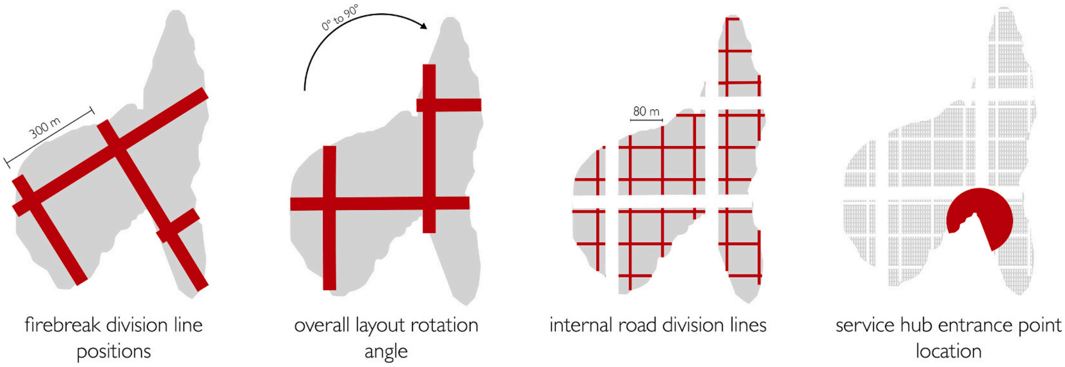

Fig. 3. Model optimisation parameters.

from 0° to 90°), and (4) service hub entrance point location (Fig. 3). These variables generate a search space of approximately 4×10^6 possible combinations, calculated based on the discrete and continuous ranges. This search space scale justifies the use of automated evolutionary optimisation, as exhaustive manual exploration would be computationally infeasible and temporally unrealistic for post-disaster planning contexts.

The optimisation process was configured with a population size of 50 individuals per generation and a total of 50 generations, yielding 2500 evaluated design alternatives. These parameter values were informed by previous optimisation studies in urban and architectural design contexts [43–45], which demonstrate that population sizes of 40–60 and generation counts of 40–60 typically achieve Pareto Front convergence for multi-objective spatial configuration problems with similar complexity. The population size of 50 balances exploration (maintaining sufficient diversity to discover varied regions of the design space) with computational efficiency (larger populations extend simulation time proportionally). Additionally, Wallacei Analytics®'s built-in simulation time estimator was consulted during parameter selection to ensure computational feasibility within the research objectives. Algorithm parameters followed Wallacei Analytics®'s default settings derived from NSGA-II literature: crossover probability of 0.9 (high rate promotes solution recombination), mutation probability of 1/n, where n is the number of genes (adaptive rate prevents premature convergence), crossover distribution index of 20, and mutation distribution index of 20 (controlling the spread of offspring around parent solutions). These defaults represent established best practices for NSGA-II applications and were retained to leverage validated parameter configurations rather than conducting extensive problem-specific tuning, which would have consumed additional time without guaranteed performance improvements.

The optimisation simulation was executed on an Intel Core i7-8750H processor (2.20 GHz, 16 GB RAM), requiring approximately 81 h to evaluate all 2500 design alternatives. While this computational duration may initially appear lengthy for urgent post-disaster contexts, it remains operationally viable for several reasons. First, the timeline for establishing temporary housing areas includes site designation, environmental assessment, clearance, levelling, and infrastructure installation (utility connections, drainage systems), processes that typically require days to weeks, even under emergency mobilisation [32]. The computational analysis can proceed in parallel with these preparatory activities, utilising the lead time before physical shelter deployment begins. Second, the 81-h investment produces a comprehensive set of optimised alternatives spanning the full Pareto Front, enabling stakeholders to rapidly evaluate trade-offs and select context-appropriate solutions, a decision process far more efficient than iterative cycles of manual design, stakeholder review, and revision that characterise conventional planning approaches. Third, once the parametric framework is established, it can be rapidly reapplied to alternative sites by adjusting only the boundary geometry input, amortising the initial methodological development effort across multiple deployment scenarios. Additionally, a better technological infrastructure can also eliminate the time problem.

4. Results

The optimisation process generated 2500 design alternatives over 50 generations, from which 50 Pareto-optimal solutions were identified. Results presentation proceeds in three stages: first, representative initial alternatives illustrate how design parameters shape spatial configurations (Fig. 4); second, statistical analysis of all 50 Pareto solutions quantifies the trade-off relationship (Table 2); third, a matrix of 16 Pareto-optimal solutions reveals capacity-accessibility trade-off patterns (Fig. 5).

4.1. Design explorations through parametric modelling

The parametric framework developed in this study generates spatial layouts by systematically manipulating design parameters derived from humanitarian standards, producing diverse configurations that comply with regulatory constraints while exhibiting distinct geometric characteristics. Fig. 4 illustrates six key parameters whose variation drives spatial differentiation across generated alternatives: firebreak positioning and dimensional specifications, overall layout rotation, road network configuration, shelter block formation patterns, individual container placement logic, and service area location paired with site entrance positioning. These parameters represent the primary design degrees of freedom encoded in the algorithmic framework, each governed by rules extracted from the standards, while permitting controlled variation to explore alternative spatial strategies.

Firebreak positioning and overall rotation establish the layout's fundamental geometric organisation. Firebreak alternatives demonstrate how the universal 30-m width standard at 300-m intervals can be satisfied through diagonal configurations aligned with varied site axes, Fig. 4.1- a, b or adaptive arrangements responding to irregular boundaries, Fig. 4.1-c. These positioning strategies ruled through subsequent design decisions by defining the primary spatial subdivision logic. Layout rotation alternatives span from near-orthogonal orientations, Fig. 4.2-c: ~0–90°, through moderate angles, Fig. 4.2-b: ~30°, to clear diagonals, Fig. 4.2-a: ~45°, determining how shelter blocks and circulation networks engage with site boundaries.

Road network configuration and block formation patterns mediate between global layout orientation and local unit placement. Road alternatives exhibit varied organisational strategies: dense irregular grids adapting to boundary geometries(Fig. 4.3-a,b,c), regular orthogonal networks prioritising circulation clarity, or hierarchical systems differentiating primary and secondary routes. These circulation choices directly influence block formation possibilities, with alternatives

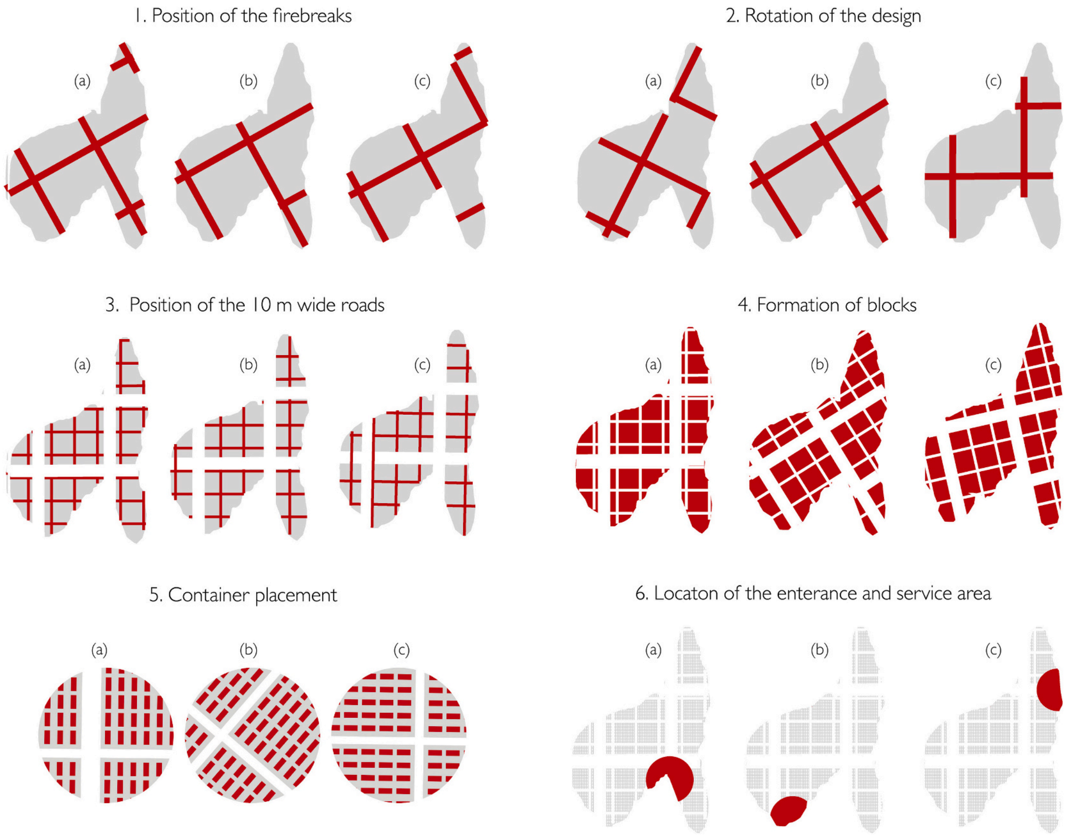

Fig. 4. Multiple design variations across parameters to illustrate the generative capacity of the algorithmic framework.

ranging from orthogonal clusters maintaining geometric regularity, Fig. 4.4-a, to diagonal arrangements at ~45°, Fig. 4.4-b or boundary-adaptive irregular blocks illustrated in Fig. 4.4-c. The orthogonal-diagonal contrast evident across these rows reflects a fundamental design tension: regular geometries simplify construction and circulation legibility but may sacrifice buildable area when site boundaries are irregular, while adaptive strategies maximise area utilisation at the cost of geometric complexity.

Container placement orientations (Fig. 4.5) and service area locations (Fig. 4.6) represent fine-scale and accessibility-critical parameters. At the unit level, containers can be arranged in vertical/horizontal alignments, diagonal configurations, or mixed/staggered patterns (Fig. 4.5-a,b,c, respectively), with orientation choices affecting internal circulation, visual privacy, and solar exposure. Service area positioning emerges as the most direct determinant of accessibility outcomes: centralised placements near the site's geometric centre (Fig. 4.6-a: bottom-centre) minimise maximum walking distances across all zones, while off-centre (Fig. 4.6-b) or peripheral edge positions (Fig. 4.6-c: top-right) free central areas for dense shelter clustering but increase average pedestrian distances.

The combined nature of these parameters generates an expansive and exploratory design space with each parameter possessing multiple discrete values or continuous ranges; the total number of theoretically possible configurations reaches several million. However, not all combinations produce viable layouts, as geometric constraints, boundary conditions, and standard requirements eliminate infeasible configurations during generation. The optimisation process systematically navigates this reduced but still extensive solution space, evaluating 2500 distinct alternatives over 50 generations to identify the 50 Pareto-optimal solutions that represent non-dominated trade-offs between capacity and accessibility objectives. Importantly, all generated alternatives maintain compliance with the humanitarian standards, ensuring that geometric diversity emerges from legitimate parameter flexibility rather than standards violation.

The alternatives shown in Fig. 4 exemplified configurations generated during early optimisation phases, illustrating the algorithm's capacity to produce geometrically diverse layouts before performance-based selection. These variations are not necessarily high-performing solutions but rather demonstrate the breadth of spatial possibilities the framework can generate from a common set of humanitarian standards and site boundaries.

4.2. Model performance

Quantitative analysis of all 50 Pareto-optimal solutions (Table 2) reveals the trade-off bounds and distribution characteristics across the solution space. Shelter capacity ranges from 1222 to 1737 units, with a mean: 1452, median: 1459, SD: 86.6, while accessibility rates span 18.8% to 92.0%, with a mean: 47.1%, median: 50.2%, SD: 20.7%. The substantial standard deviations in both metrics reflect the Pareto Front's breadth, indicating that solutions are distributed across the trade-off spectrum rather than clustered around a single compromise. The maximum capacity of 1737 units represents a 42% increase over the minimum, yet this capacity gain corresponds to reducing accessibility from 92.0% to approximately 19–25%, quantifying the fundamental tension between population accommodation and service proximity.

Accessible unit counts exhibit particularly high variability, ranging from 276 to 1177 units meeting the 500-m criterion. This wide range

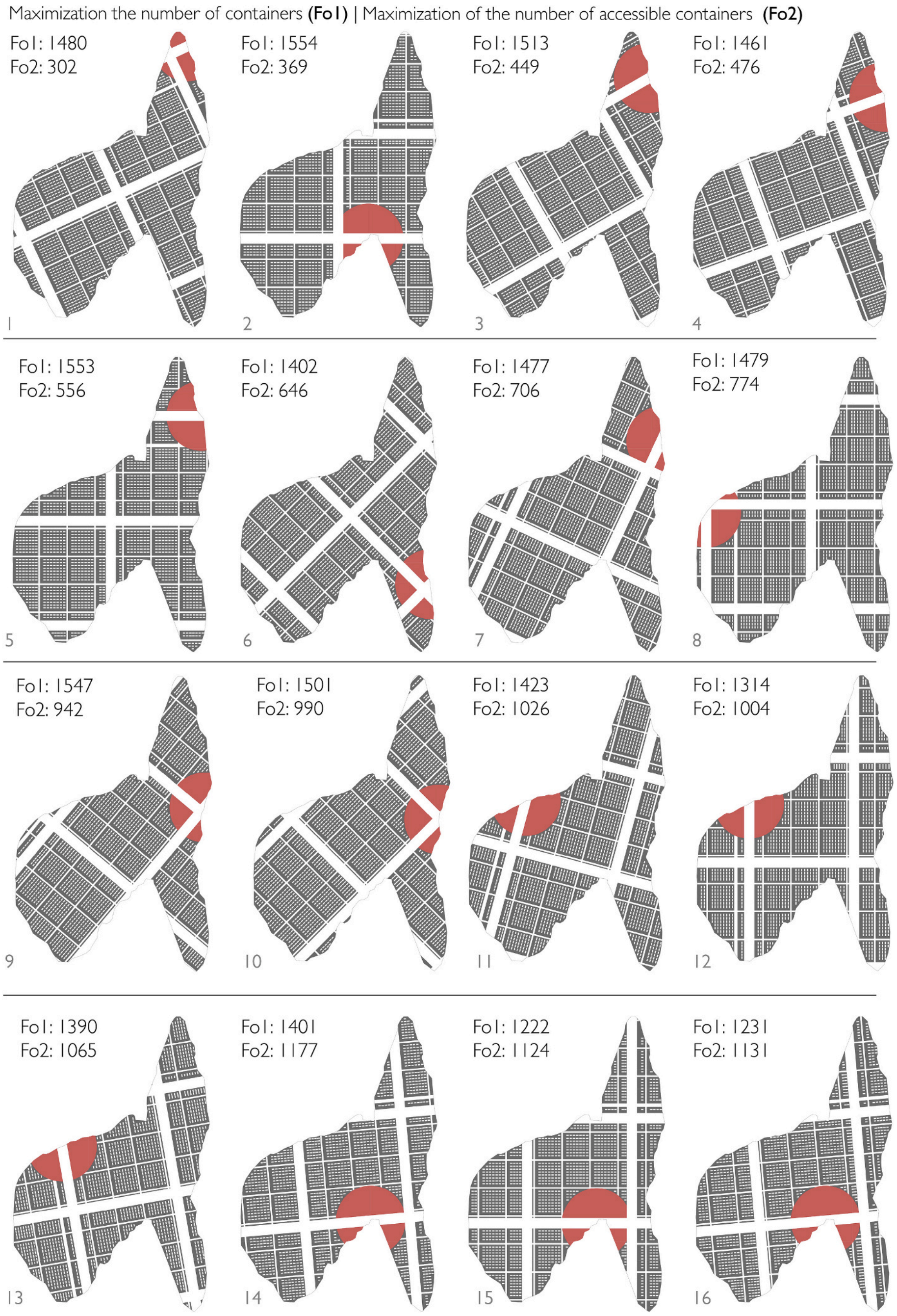

Fig. 5. Sixteen Pareto-optimal solutions arranged by increasing accessibility. Each cell displays site layout with performance metrics. Red indicates service areas, white indicates individual shelter units, and grey indicates shelter blocks/clusters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Descriptive statistics of 50 Pareto-optimal solutions showing performance distributions for shelter capacity, accessible units, and accessibility rates.

Metric ($n = 50$)	Min	Max	Mean	Median	Standard Deviation (SD)
Shelter capacity (units)	1222	1737	1451.60	1459	86.59
Accessible units (count)	276	1177	671.52	755	267.49
Accessibility rate (%)	18.8	92	47.1	50.2	20.7

demonstrates that absolute accessibility performance depends on both total capacity and spatial strategy: a 1500-unit configuration at 50% accessibility provides 750 accessible units, while a 1300-unit alternative at 57% delivers only 741 accessible units despite its higher percentage. The median values (capacity: 1459, accessibility: 50.2%) approximate means, indicating relatively symmetric distributions without extreme skewness toward either capacity-maximising or accessibility-maximising endpoints, confirming comprehensive Pareto Front coverage.

4.3. Spatial configurations across the pareto front

Fig. 5 presents 16 Pareto-optimal solutions selected from the 50 identified alternatives to represent distinct spatial strategies while spanning the accessibility spectrum. Selection made randomly and prioritised visually diverse configuration approaches across the performance range, avoiding redundant near-identical layouts with marginal differences. Solutions are ordered by accessibility ratio, progressing from 20.4% (Cell 1: 1480 units, 302 accessible) to 91.9% (Cell 16: 1231 units, 1131 accessible). This progression reveals the fundamental capacity-accessibility trade-off: improving accessibility from approximately 20% to 92% requires reducing total shelter capacity by 249 units, representing a 16.8% density reduction. One could argue that the trade-off relationship also exhibits non-linear characteristics, with accessibility gains becoming progressively more costly in terms of capacity sacrifice. Initial improvements from 20% to 60% accessibility (Cells 1–9) incur relatively modest capacity reductions of 86 units (5.8%), while advancing from 60% to 92% (Cells 9–16) requires sacrificing an additional 233 units (15.0%), demonstrating diminishing returns as accessibility approaches optimal levels.

Spatial configuration analysis across the solution spectrum reveals systematic patterns linking layout strategies to performance outcomes. Service hub positioning emerges as a critical determinant of accessibility performance: solutions prioritising accessibility (Cells 13–16) consistently position service hubs near the site's geometric centre, minimising maximum walking distances across all shelter zones. Conversely, capacity-maximising solutions (Cells 1–4, 6, 8) position service hubs toward site edges or entry points, freeing central areas for dense shelter clustering but increasing average pedestrian distances. This pattern exhibits limited exceptions, notably Cell 2, which achieves moderate accessibility despite non-central hub placement through compensating geometric strategies. Cells with edge-positioned service hubs (3, 5, 7, 9) demonstrate the trade-off consequences most clearly: while achieving high total unit counts (1477–1553 units), their accessibility rates remain constrained (30–61%) due to peripheral service locations requiring longer walking distances for centrally located shelters.

Layout orientation patterns further differentiate solution characteristics. High-accessibility configurations (Cells 14, 15, 16) exhibit predominantly orthogonal geometries with shelter blocks aligned to primary axes, facilitating clear circulation hierarchies and direct paths between shelters and centralised service hubs. This orthogonal organisation supports balanced spatial distribution, enabling consistent accessibility across the site. In contrast, lower-accessibility solutions display more varied orientations and irregular cluster arrangements, prioritising opportunistic placement to maximise buildable area utilisation over systematic accessibility optimisation. Service hub dimensions also vary systematically with accessibility performance: higher-accessibility solutions allocate larger service areas, while capacity-focused solutions compress service footprints to reserve more area for shelter placement, though this compression indirectly constrains accessibility by reducing service capacity and potentially increasing internal congestion.

Analysis of mid-spectrum solutions (Cells 7–12) reveals a transition zone where competing objectives achieve relative balance. These configurations maintain total capacities between 1402 and 1553 units while achieving accessibility rates of 46–76%, representing compromises where neither objective dominates design logic. Spatial strategies in this zone combine elements of both extremes: service hubs positioned at intermediate distances from site centres, mixed orthogonal and diagonal block orientations, and varied service area sizes. This variability suggests that multiple spatial strategies can achieve similar performance within the balanced range, providing decision-makers with flexibility to prioritise secondary considerations such as cultural preferences, phasing strategies, or site-specific constraints when selecting among equivalently performing alternatives.

Block typology and clustering patterns vary across solutions without exhibiting strict correlation to accessibility performance, indicating that unit arrangement within clusters represents a secondary design parameter relative to service hub placement and overall layout organisation. Solutions across the accessibility spectrum employ diverse cluster configurations, suggesting that local-scale shelter arrangement can be adapted to accommodate cultural requirements, family sizes, or community preferences without fundamentally compromising site-scale accessibility outcomes, provided that primary circulation networks and service hub positioning adhere to accessibility-optimising principles.

5. Discussion

This study develops a computational framework integrating parametric modelling with multi-objective evolutionary optimisation to generate temporary housing layouts that systematically reconcile conflicting humanitarian spatial standards. Applied to Ümraniye National Garden, a pre-designated 15-ha temporary housing site in Istanbul, the framework produced 2500 design alternatives through automated exploration of layout configurations, identifying 50 Pareto-optimal solutions that represent non-dominated trade-offs between shelter capacity and pedestrian accessibility to essential services. The current section situates these contributions within existing computational humanitarian design literature, examines observed patterns in the generated solutions, addresses implementation and governance considerations for practical adoption, and identifies limitations and future research directions.

5.1. Reconciling standards and urban complexity

The computational humanitarian design literature has evolved from unit-scale optimisation [7,9] toward site-scale layout generation, yet critical gaps persist in standards integration and holistic configuration. This study's primary contribution relative to prior work lies in three areas: systematic operationalisation of conflicting multi-source standards, holistic site layout generation rather than component optimisation, and explicit trade-off exploration through Pareto-based methods. Andriasyan et al. [11] represent a similar approach, developing an algorithmic framework for refugee camps that automates plot generation and applies genetic optimisation to WASH facility placement. Their work demonstrates computational design's potential in humanitarian contexts and addresses fire safety through graph-based propagation analysis. However, their approach assumes pre-established UNHCR standards without addressing divergences across frameworks, optimises specific facility subsystems rather than generating complete integrated layouts, and does not systematically explore trade-offs between competing site-scale objectives such as capacity versus accessibility. This study extends their work by encoding standards from four sources (SPHERE, UNHCR, AFAD, CUP), explicitly reconciling conflicts and treating the entire site configuration (road networks, firebreaks, service hubs, shelter clusters) as an integrated optimisation problem rather than optimising components sequentially. Daher et al. [10] and Daher and Kubicki [29] advance participatory computational design for camp planning, emphasising stakeholder engagement in parameter setting. Their framework represents an important methodological innovation in democratising algorithmic design processes. However, their model relies on designer-defined spatial rules without systematic derivation from documented humanitarian standards, limiting its replicability across contexts where different standards apply. By extracting and synthesising different standards, this research provides a systematic, evidence-based method for parameter definition that complements participatory approaches: standards establish baseline constraints within which stakeholder preferences can be explored. Future integration of both approaches would enable standards-compliant participatory design. More broadly, the extensive review by Perrucci and Baroud [6] identifies that existing decision support tools predominantly evaluate or rank predefined alternatives using methods such as AHP, TOPSIS, or cost-benefit analysis. While these tools support selection among manually designed options, they do not generate spatial configurations. Our approach addresses this gap by producing the alternatives themselves, shifting the decision-support function from “which predefined layout is best?” to “which layout from thousands of generated possibilities best suits our priorities?” This generative capacity fundamentally changes the designer's role from producing a single proposal to curating a solution space and supporting stakeholders in navigating trade-offs.

5.2. *Observed patterns and trade-off characteristics in generated solutions*

Analysis of the 2500 generated alternatives and 50 Pareto-optimal solutions reveals several patterns that point out the capacity-accessibility trade-off structure and inform practical deployment decisions. The Pareto Front demonstrates that shelter capacity and 500-m accessibility exist in fundamental tension: the capacity range spans 1222 to 1737 units (42% variation), while accessibility rates range from 18.8% to 92.0% (73-percentage-point span). Configurations prioritising a capacity approach to the 1737-unit maximum but achieve only 19–25% accessibility, positioning most shelters beyond the 500-m service threshold. Conversely, configurations maximising accessibility (exceeding 85%) accommodate populations below 1350 units, sacrificing approximately 400 units (23% capacity reduction) to ensure service proximity for the majority of residents. The trade-off exhibits non-linear characteristics: initial accessibility improvements from 20% to 60% cost relatively modest capacity reductions (∼6%), while advancing from 60% to 92% requires substantially greater sacrifices (∼15%), demonstrating diminishing returns as accessibility approaches optimal levels.

Spatial configuration analysis across the 16 examined Pareto-optimal solutions reveals systematic patterns linking layout strategies to performance outcomes. Accessibility-optimising configurations (Cells 13–16, achieving 76–92% accessibility) consistently position service hubs near the site's geometric centre, minimising maximum walking distances across all shelter zones. Capacity-maximising configurations (Cells 1–5, accommodating 1477–1554 units) position service hubs toward site edges or entry points, particularly evident in Cells 3, 5, 7, and 9, freeing central areas for dense shelter clustering but increasing average pedestrian distances. High-accessibility solutions (Cells 14–16) also exhibit predominantly orthogonal geometries with shelter blocks aligned to primary axes, facilitating clear circulation hierarchies and direct paths between shelters and centralised service hubs. This orthogonal organisation supports balanced spatial distribution, enabling consistent accessibility across the site. These observed patterns suggest that service hub centrality represents the most critical single parameter for accessibility performance, while capacity maximisation relies on opportunistic peripheral service placement combined with aggressive internal densification strategies.

However, the generated alternatives also exposed geometric edge cases where algorithmic rule application produces suboptimal local conditions. In highly concave boundary regions, road networks occasionally terminate abruptly, or firebreaks misalign with building clusters, creating isolated zones with compromised circulation. These instances reflect the inherent tension between universal rule-based generation and site-specific topological irregularities. Rather than representing algorithmic failures, these edge cases highlight the complementary roles of computation and human judgment: algorithms rapidly generate near-optimal global configurations, while human review addresses localised geometric conflicts requiring site-specific expertise. In practice, this produces a workflow where the computational investment generates a shortlist of high-performing layouts requiring minor manual refinement, substantially more efficient than iterative manual design cycles that typically span weeks for a single layout proposal.

5.3. *Reconciling standards across institutional and cultural contexts*

The comparative analysis in Section 2.3 revealed significant divergences in spatial parameters across humanitarian frameworks despite consensus on fundamental safety measures. All examined sources prescribe 30-m firebreaks at 300-m intervals and a minimum 3-m elevation above water, reflecting universal risk mitigation priorities. However, divergences emerge in operational details: SPHERE and UNHCR recommend 2-m lateral setbacks between units, while the CUP specifies 6-m cluster separations; international frameworks omit road width specifications, while AFAD and the Chamber define 10–15 m standards; only the Chamber establishes a maximum 500-m service accessibility threshold. These differences reflect institutional priorities rather than contradictions: international frameworks prioritise flexibility to accommodate diverse contexts, deliberately leaving certain parameters unspecified for local adaptation, while national frameworks provide prescriptive guidance that accelerates decision-making within specific regulatory environments.

Our parametric model addresses this plurality by treating standards as adjustable parameters rather than fixed constraints. This design philosophy acknowledges that humanitarian response involves multiple stakeholders with varying authority: international agencies (UNHCR, IFRC) provide technical guidance, national disaster management authorities (e.g., AFAD) hold regulatory jurisdiction, and professional associations (e.g., CUP) offer contextual expertise. Rather than imposing a single *correct* standard set, the framework enables decision-makers to prioritise specific frameworks or create hybrid rule combinations appropriate to their institutional context and operational mandate. For instance, a municipal planner implementing a site under AFAD jurisdiction could prioritise national standards while consulting international guidelines for unspecified parameters, whereas an international NGO might reverse these priorities in a cross-border response.

Such flexibility has the potential to extend to cultural and contextual adaptation. While the current implementation uses AFAD's standard container dimensions (3 × 7 m) and the CUP's 8-unit cluster configuration, the parametric logic can accommodate alternative unit types (tents, prefabricated modules, locally sourced materials) and spatial arrangements (courtyard configurations, gender-segregated zones, extended family clusters) by modifying input parameters without restructuring the underlying algorithmic framework. However, this technical adaptability does not fully address the deeper challenge of operationalising culturally specific spatial needs into quantifiable parameters. How should the algorithm encode preferences for communal cooking spaces, prayer areas, or children's play zones when standards documents remain silent on such dimensions? This limitation points toward the necessary integration of participatory design methods where community representatives directly manipulate parameters or evaluate generated alternatives, ensuring cultural appropriateness alongside standards compliance [29].

5.4. *Implementation considerations: institutional integration and governance*

Translating this computational framework from research demonstration to operational practice requires addressing institutional, technical, and governance dimensions that determine real-world adoption. Here, we populated several implementation pathways that merit consideration, each with distinct advantages and barriers.

5.4.1. *Institutional actors and use contexts*

The framework's primary potential users span multiple organisational types with different operational mandates. National disaster management agencies (e.g., AFAD in Türkiye, Federal Emergency Management Agency (FEMA) in the United States) responsible for coordinating large-scale disaster response could integrate the tool into pre-disaster preparedness planning, generating optimised layouts for all pre-designated temporary housing sites within their jurisdiction and maintaining a library of ready-to-deploy configurations. This proactive application leverages the framework's computational requirements during non-emergency periods, eliminating time pressure. Municipal urban planning departments could employ the tool during site designation processes, evaluating how different parcels perform under standards-compliant layout generation before finalising site selections, effectively coupling site selection with layout feasibility analysis. International humanitarian organisations (UNHCR, IFRC, IOM) operating across diverse contexts could use the framework's adaptability to rapidly configure layouts when deploying to new crisis zones, adjusting parameters to reflect local standards, available shelter types, and cultural requirements.

5.4.2. *Integration with existing workflows*

Current temporary housing planning practices typically involve manual CAD drafting by architects or engineers working from humanitarian handbook guidelines, producing one or two layout proposals for stakeholder review. The computational framework does not replace this expertise but augments it by front-loading the exploration phase: rather than designers manually drafting multiple iterations, the algorithm generates thousands of standards-compliant alternatives, and designers curate high-performing options for detailed development and stakeholder presentation. This workflow shift requires computational infrastructure (relevant software, adequate computing hardware) and personnel training in parametric modelling concepts [28]. While these requirements present barriers for resource-constrained organisations, the increasing availability of cloud computing and open-source parametric tools may lower adoption thresholds over time.

5.4.3. *Data requirements and availability*

The framework requires three primary data inputs: site boundary geometry (obtainable from municipal GIS databases, satellite imagery, or field surveys), applicable spatial standards (documented in UNHCR, SPHERE, and national regulations), and context-specific parameters (available shelter unit dimensions, target population size). In well-prepared contexts such as Istanbul, where sites are pre-designated and digitally mapped, data acquisition is straightforward. However, in sudden-onset disasters in data-scarce environments, rapid site boundary digitisation becomes critical. The widespread adoption of OpenStreetMap for humanitarian response [5] provides a potential data pipeline: field teams using mobile mapping tools can rapidly trace site boundaries, enabling near-immediate algorithmic application. The framework's reliance on documented standards as primary inputs also raises questions about contexts where formal standards are absent, contested, or culturally inappropriate, necessitating methods for encoding tacit or community-defined spatial requirements.

5.4.4. *Governance and decision authority*

A critical implementation question concerns who holds authority to select among generated alternatives and whether algorithmic recommendations influence or override human judgment. The Pareto Front presentation deliberately avoids prescribing a single optimal solution, instead empowering stakeholders to navigate trade-offs according to their priorities. However, this design philosophy assumes stakeholders possess sufficient technical literacy to interpret multi-objective optimisation outputs and sufficient institutional autonomy to exercise judgment. In hierarchical organisational contexts or politically charged post-disaster environments, algorithmic outputs might be misinterpreted as objective technical mandates rather than decision-support tools, potentially constraining participatory deliberation. Clear communication that the framework generates possibilities rather than prescriptions, and that human judgment remains essential for addressing dimensions the algorithm cannot capture (social cohesion, psychological well-being, power dynamics), is critical for responsible implementation.

5.5. *Limitations and future research*

Several limitations framed the scope and applicability of this work, pointing toward necessary extensions for comprehensive humanitarian shelter planning support. First, the framework addresses internal site layout generation but does not integrate site selection, assuming site boundaries as given inputs. While this focus aligns with the research gap identified in existing literature [6], comprehensive decision support would couple layout generation with site suitability analysis. Future work could integrate GIS-based multi-criteria site evaluation, iteratively assessing how different candidate sites perform under optimised layout generation, effectively asking “which site enables the best achievable layout outcomes?” rather than treating site selection and layout design as sequential independent processes. Also, the current implementation abstracts site topography, vegetation, and existing infrastructure, assuming cleared and levelled ground. While justified for research focus and operationally realistic given standard site preparation practices, this simplification limits applicability to contexts where site modification is infeasible due to environmental regulations, budget constraints, or compressed timelines. Extending the framework to incorporate topographic constraints (slope-based buildability limits, cut-and-fill cost modelling) and existing infrastructure (preserving mature trees, integrating existing roads, avoiding underground utilities) would enhance practical relevance. Such extensions would likely increase computational complexity, necessitating the optimisation strategies mentioned above. Another possible development point is to add practitioner and community feedback in the framework's development. The study has not incorporated input from disaster management professionals or affected communities whose experiences inform needs beyond quantifiable metrics. Future work should integrate participatory design methods enabling stakeholders to encode cultural preferences and evaluate alternatives against qualitative criteria such as social cohesion and psychological appropriateness. We believe that prospective validation studies with disaster management agencies would enable comparative assessment under realistic conditions, providing empirical evidence of operational advantages and identifying context-specific implementation barriers.

6. Conclusion

This study demonstrates that systematic computational operationalisation of different humanitarian spatial standards can enable parametric generation of optimised temporary housing layouts under post-disaster time constraints. By extracting and reconciling parameters from four frameworks (SPHERE, UNHCR, AFAD, CUP), the research addresses a critical gap between evaluation-focused decision support tools and the generative design capacity needed for holistic site configuration. Applied to Istanbul's Ümraniye National Garden, the parametric framework produced 2500 layout alternatives and identified 50 Pareto-optimal solutions spanning capacity-accessibility trade-offs, demonstrating that algorithmic exploration can systematically navigate design spaces containing millions of possible configurations while maintaining standards compliance across divergent institutional requirements.

The framework's contribution extends beyond technical demonstration to reveal fundamental characteristics of humanitarian shelter planning as a computational problem. The observed trade-off structure quantifies previously implicit design tensions, demonstrating how accessibility improvements require progressively greater capacity sacrifices as performance approaches optimal levels. Spatial pattern analysis revealing service hub centrality as the primary accessibility determinant illustrates how systematic computational exploration uncovers design principles applicable across similar site contexts. Simultaneously, geometric edge cases in concave boundary regions expose computation's boundaries, affirming that algorithms excel at global optimisation while human judgment remains essential for refinement and dimensions resisting quantification, such as cultural appropriateness, social cohesion, and participatory engagement.

Implementation viability depends on institutional integration pathways that position the framework as an augmentation rather than a replacement of existing expertise. National disaster agencies could leverage the tool during pre-disaster preparedness to generate ready-to-deploy configurations for pre-designated sites, eliminating computational time pressure. Municipal planners could couple layout generation with site selection to evaluate feasibility before land designation. International organisations could adapt the framework's parametric flexibility to diverse cultural contexts and shelter typologies. However, responsible deployment requires addressing governance questions about decision authority, ensuring algorithmic outputs inform rather than constrain participatory processes, and building computational literacy within humanitarian professional communities.

Future research must address persistent limitations in operationalising qualitative humanitarian dimensions beyond capacity and accessibility, integrating site selection with layout generation to enable coupled decision-making, reducing computational overhead for interactive stakeholder workshops, and developing systematic methods for encoding community preferences alongside documented standards. As climate change intensifies disaster frequency and urban expansion concentrates vulnerable populations in hazard-prone regions, hybrid human-AI systems that leverage computation's systematic exploration capacity while preserving human judgment for value negotiation and cultural context will become increasingly vital. This study provides empirical evidence that such systems are technically feasible, operationally viable within realistic constraints, and capable of producing demonstrable improvements over manual planning workflows, contributing a replicable foundation for future advances in computational humanitarian response.

CRediT authorship contribution statement

Merve Deniz Tak: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mert Akay:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

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

During the preparation of this work, the author used ChatGPT and DeepL in order to improve language and readability. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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