European Journal of Geography

The publication of the European Journal of Geography (EJG) is based on the European Association of Geographers' goal to make European Geography a worldwide reference and standard. Thus, the scope of the EJG is to publish original and innovative papers that will substantially improve, in a theoretical, conceptual, or empirical way the quality of research, learning, teaching, and applying geography, as well as in promoting the significance of geography as a discipline. Submissions are encouraged to have a European dimension. The European Journal of Geography is a peer-reviewed open access journal and is published quarterly.

Received: 03/11/2024

Revised: 17/01/2025

Revised: 23/02/2025

Accepted: 05/03/2025

Published: 15/03/2025

Academic Editor:
Dr. Alexandros Bartzokas-Tsiompras

DOI: 10.48088/ejg.m.bat.16.2.052.065

ISSN: 1792-1341

Research Article

Incorporating Population Dynamics in the Context of Earthquake Shelter Location-Allocation Analysis

Marios Batsaris[1]✉

[1] University of the Aegean, Greece

✉ Correspondence: m.batsaris@aegean.gr

Abstract: Location-allocation is a widely used approach to optimally select earthquake shelters and efficiently allocate the population in case of an emergency. A significant limitation often ignored by the vast majority of studies is the utilization of static aggregations of residential population, which may lead to sub-optimal location decisions and inefficient allocations. To overcome this limitation, in this article, an attempt to spatially refine population data, as well as, to capture population fluctuations throughout the day, using areal interpolation methods along with open spatial information, is undertaken. Then, its influence on the shelter location selection and population allocation process is examined. The city of Mytilini, Lesvos, Greece is used as the case study to further investigate three location-allocation scenarios using block-level census population, building-level night and day estimations as input. The results indicate that using spatially refined population data provide reduced distances, better shelter selection and capacity optimization, and finally, more efficient allocations. Moreover, using building-level day estimations of the population distribution reveals significant shifts in sheltering demand from residential areas to mixed and commercial zones. The use of detailed population dynamics data can give insights about the adequacy of shelter provision under different scenarios, and therefore, help civil protection authorities to make much more informed decisions.

Keywords: population dynamics; areal interpolation; location-allocation; earthquake shelter location

Highlights:

- Areal interpolation using ancillary information can be used to capture population dynamics.
- Building-level population data in the context of location-allocation provide reduced distances, better shelter selection and capacity management, and efficient allocations.
- Daytime building-level population indicates significant shifts of sheltering demand.

1. Introduction

Earthquakes are among the most destructive natural disasters, significantly impacting life, urban infrastructure, and socio-economic stability of the affected areas. Moreover, earthquakes pose several challenges to communities because of their unpredictable and violent nature. After the occurrence of a disastrous earthquake, panic and uncertainty often drive the population to leave indoor premises towards safer, open spaces (L. Zhao et al., 2017). These open spaces can provide temporary shelter and basic life support services such as water, electricity, and sanitation until the risk is minimized (Ma et al., 2019). Additionally, they must be resilient to earthquakes and their potential side effects, as well as, to be easily accessible, in a reasonable time frame (Anhorn & Khazai, 2015). Therefore, it is important for civil protection authorities to carefully select these locations that will be used as emergency evacuation shelters to protect the population in the wake of earthquakes.

Location-allocation analysis has been extensively applied in this direction (Chang et al., 2024; Kaveh et al., 2020; Ma et al., 2019; Tang & Osaragi, 2024; Wang et al., 2021). Given a set of facilities, a set of individuals, a space in which they co-exist and a metric system for cost measuring (distance, time, fuel consumption etc.) (ReVelle & Eiselt, 2005), location-allocation aims to locate the facilities and assign individuals in a way that satisfies an objective function (Scott, 1970). Accurate and detailed population data play a pivotal role in earthquake shelter location-allocation analysis, as they determine where facilities are most needed, and influence the efficiency of allocations (Zhang et al., 2020). Census is a common source of population data. However, its use poses two notable limitations in terms of its spatial and temporal characteristics. Due to statistical confidentiality concerns, census releases population and other socio-economic variables in a form of spatially aggregated spatial units such as communes or city blocks (Tenerelli et al., 2015). Furthermore, census data are also temporally constrained as they represent a static snapshot of the population at the place of residence (Bhaduri et al., 2007). The evolution of Geographic Information Systems (GIS) and Spatial Analysis provide tools and methods to accurately refine spatial and temporal granularities of census data.

Areal interpolation can be used in this direction as it is suitable for aggregated data (Lam, 1983). Areal interpolation may be defined as the process of transforming population data from a set of coarse spatial zones (source) to a detailed one (target) (Mennis, 2003). A large number of methods have been reported in the scientific literature. Many of them depend solely on source and target data, while others utilize additional information to guide the interpolation process (Comber & Zeng, 2019; Wu et al., 2005). To the best of our knowledge, the vast majority of existing location-allocation approaches for earthquake shelter decisions, mainly rely on static residential (night) population data acquired from censuses (Chen et al., 2013; Dehnavi Eelagh & Ali Abbaspour, 2024; Geng et al., 2021; Hu et al., 2012; Kilci et al., 2015; J. Xu et al., 2016; X. Zhao et al., 2015) which often lack the spatial and temporal granularity required to support earthquake shelter location decisions in urban environments. In small scale applications, aggregated census data may be insufficient to efficiently address location-allocation decisions. Therefore, one may need to use areal interpolation methods to transform census data into a finer scale. Ye et al. (Ye et al., 2012) transformed community-level population counts in the granularity of buildings based on building size and occupancy (enhanced volumetric approach), aiming to improve shelter accessibility and optimization of evacuation destinations in Pudong, Shanghai, China. Batsaris et al. (Batsaris et al., 2019) also used areal interpolation with ancillary information to identify building occupation in order to refine block-level census data down to individual buildings. The results were then used to perform location-allocation analysis for earthquake shelters in the city of Mytilini, Lesvos, Greece.

However, earthquakes can occur at any time and thus, it is important to capture population fluctuations throughout the day (Bian & Wilmot, 2015; Freire & Aubrecht, 2012a). Areal interpolation using ancillary information may be also used to capture population distribution fluctuations (Freire & Aubrecht, 2012b; Mennis, 2016). Xu et al. (W. Xu et al., 2018) estimated hourly dynamic population distributions based on nighttime and daytime population estimations in six central districts of Beijing, China. Then, performed location-allocation comparisons between a hybrid bi-level and a multi-objective approach using a modified particle swarm optimization heuristic. Zhang et al. (Zhang et al., 2020) used community scale population along with ancillary information from high-precision land use maps and Tencent User Density (TUD) big data to estimate nighttime and daytime population distributions, to perform supply-demand analysis for emergency shelters in Pudong, Shanghai, China. Nighttime population is calculated based on residential building volumes while daytime population distribution distinguishes population in stay-at-home residents, working population, students and other populations (such as tourists).

In this paper, an attempt is made to examine the influence of population granularity and dynamics in the context of earthquake shelter location-allocation. Particularly, the above research questions underlie the contribution of the study:

1. Where is the population when a destructive earthquake may occur?
2. How does the granularity of the population data may affect the location-allocation process?
3. What is the impact of using temporal estimations of the population on the location-allocation outcomes?

To address these questions, areal interpolation along with open spatial information to refine the spatial granularity and estimate temporal population distribution of the census data, is used. Then, location-allocation analysis was conducted to explore their impact on the location selection and allocation processes. To assess the efficiency and effectiveness of the proposed methods, the city of Mytilene, Lesvos, Greece, is used as the case study. The rest of the paper is structured as follows. First, the materials and methods section, provide details and information about the study area and its uniqueness, presents the data and sources utilized, and finally, discusses the methods used in this study. Second, the results and discussion section in which the outcomes are depicted and further discussed and finally, the conclusions section, provides a summary of the paper as well as, recommendations for future research.

2. Materials & Methods

2.1 Study Area

Lesvos Island lies in a very active tectonic zone with a substantial record of historical earthquakes (Zouros et al., 2011). Significant earthquakes have affected the area since 1965 with the most recent sequence occurred in 2017, peaking on June 12th, fifteen kilometers south of Lesvos with a magnitude of M6.3. This earthquake caused extended damages in the southeastern part of the island, one fatality, and 15 injuries (Chaidas et al., 2021).

In this paper, the city of Mytilini is used as the case study. Mytilini is the center of administration and commerce on the island of Lesvos, and was strategically chosen as the study area due to its significant influence over the region. It is the capital of the Lesvos prefecture and the North Aegean Region. It is situated in the southeastern part of Lesvos Island (Figure 1) and according to the 2011 Population and Housing Census, has 27,871 permanent residents. The city attracts a significant number of tourists during the summer season, as well as residents from nearby settlements who need access to various public services throughout the year. Mytilini also serves as the gateway to Lesvos Island, hosting the main port and airport of the Island.

Figure 1. Positioning of the study Area. Left: The North Aegean Region which is located in the eastern border of Greece. Middle: Lesvos Island and its position in the North Aegean Region. Right: The City of Mytilini, situated in the south-east part of the Island of Lesvos

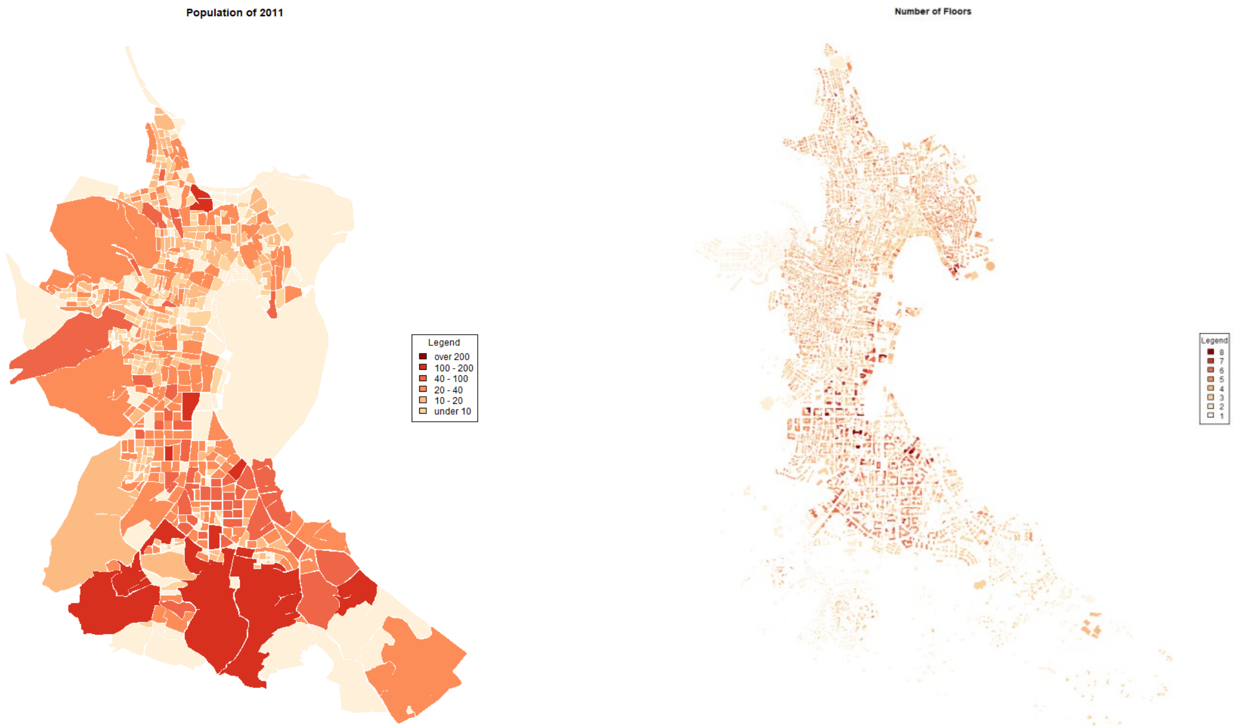
https://doi.org/10.48088/ejg.m.bat.16.2.052.065

2.2 Data and Pre-processing

In this paper, areal interpolation methods were utilized to transform census population into finer spatial and temporal scales. To accurately capture the population distribution in detail, these methods require three key datasets:

1. Source data: Block-level population counts in spreadsheet format and block-level polygons , retrieved by the Population and Housing Census of 2011 (Hellenic Statistical Authority, 2014).
2. Target data: Building-level polygons with numbers of floors, to interpolate population values to and refer to the 2001 Population and Housing Census (Hellenic Statistical Authority, 2009). The target dataset includes 10.703 individual buildings along with the number of floors of each building (Figure 2).
3. Ancillary data: Points-Of-Interest (POI) to assist the interpolation process retrieved by the OpenStreetMap © (OSM) collaborative database under the Open Data Commons Open Database License (OdbL) of the OSM foundation.

Spreadsheet population data were joined to the block polygons attribute data table using the common city block identification field. Due to data inconsistencies, 558 out of 673 city blocks are populated with 25,699 residents, and the spatial distribution of the population is depicted in Figure 2a. Most of the population is concentrated in the southern part of the city, while the northern part of the city is somewhat sparsely populated. In addition, the target dataset consists of more than 10,500 building polygons ranging from 1 to 8 floors. The vast majority of the buildings have up to 3 floors while high-rise buildings (more than 3 floors) appear in the southern part of the city, as shown in Figure 2b.



a b

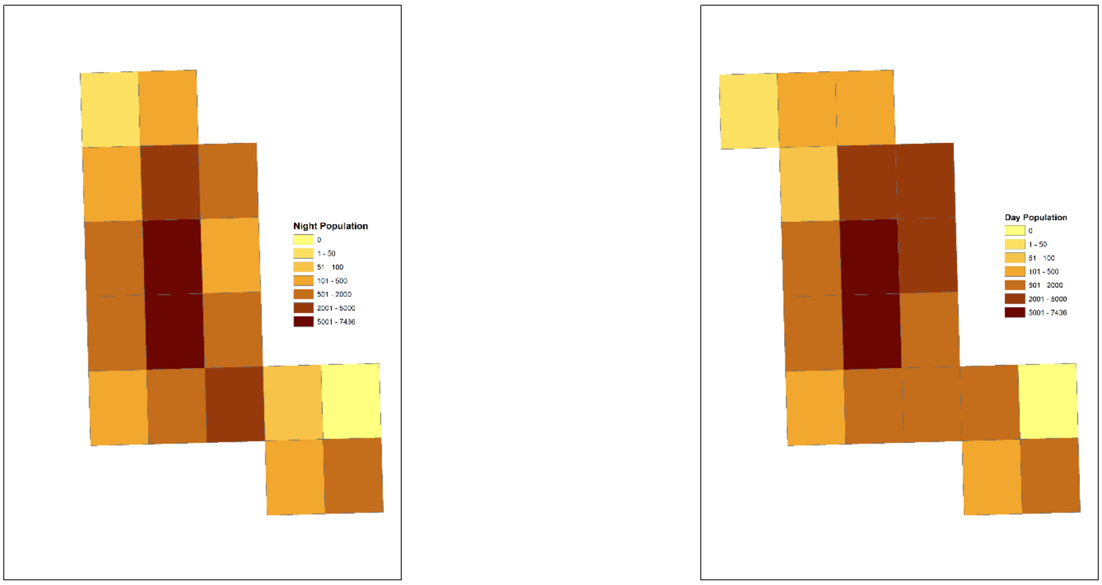
Figure 2. a) Block-level polygons of the city of Mytilini including population counts and b) Building units of Mytilini along with number of floors

OSM POI data in the study area include more than 1700 points of interest from various OSM features that indicate potential day-time activities of the population, distributed in 859 buildings.

Finally, a reference dataset was used to evaluate the accuracy of the proposed areal interpolation implementations. The dataset was retrieved by the ENhancing ACTivity and population mapping (ENACT) project, carried out by the Joint Research Centre (JRC) of the European Commission (Batista e Silva et al., 2020). The ENACT project consists of a set of 24 population grids, including one daytime and one nighttime grid for each month of the year, at 1 km^2 resolution. Population estimations were conducted using a multi-layered dasymetric mapping and a fusion of data from official statistics and other geospatial data from emerging sources. To examine the accuracy of the proposed areal interpolation methods, February night and day data of 2011 (Figure 3) as this corresponds to the month that the Greek Census of population were undertaken.

Location-allocation analysis requires three main components:

1. Shelters: A set of candidate earthquake shelters available for selection. Shelter polygons were provided by the Directorate of Emergency Policy Planning (DEPP) of Lesvos Island (Figure 4).
2. Demand: Population counts to be allocated to earthquake shelters. In the context of this study, block-level census population counts, along with detailed datasets produced through areal interpolation implementations (night and day scenarios), were used.
3. Roads: A road network dataset obtained from the OSM collaborative database (Figure 4).



a b

Figure 3. ENACT population distribution: a) night population distribution on February 2011, b) day population distribution on the same month and year

The shelter dataset is composed of 64 open spaces that can be used as emergency evacuation locations after an earthquake incident. Open spaces were provided by DEPP under certain conditions such as land use under normal conditions (school, church, hospital and university yards, open sports facilities, green urban spaces etc.), ownership status (public ownership) and accessibility (within the urban fabric).

OSM POI data and the road network were retrieved using the *osmdata* package (Padgham et al., 2017), in the R programming environment (R Core Team, 2015). The *osmdata* package extracts OSM map features through queries from the Overpass API (https://www.overpass-api.de/). Each query consists of a bounding box of the study area, the OSM map features to be extracted, and a data conversion command from XML to *simple features (sf)* (Pebesma, 2018). OSM database provides point, line and polygon data. In the context of this paper, points and polygons were used. Polygon gravitational centers (centroids) were calculated and combined with the point features into a new point dataset.

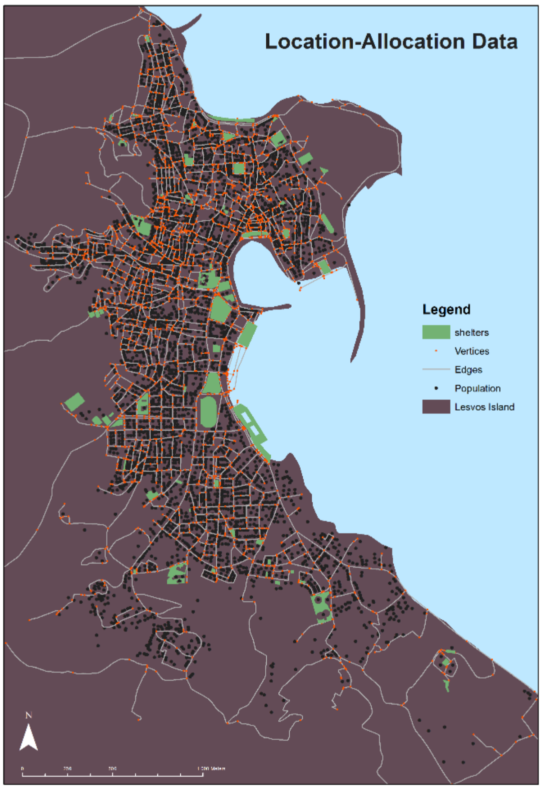


Figure 4. Data required for location-allocation analysis

2.3 Methods

2.3.1. Areal Interpolation

Areal interpolation is the process of transforming data between different spatial zones (Mennis, 2003). Areal interpolation outcomes can be significantly improved by incorporating ancillary information to guide the interpolation process, a key feature of Dasymetric mapping. Dasymetric mapping is one of the most common methods in the areal interpolation literature because it provides significantly better results by incorporating ancillary information. Ancillary information is used to identify potentially populated areas and can be found in the form of categorical layer map such as land use and land cover maps (Younes et al., 2023), mobile phone data (Bergroth et al., 2022), social media geospatial data (Bao et al., 2023), and finally, Volunteered Geographic Information (VGI) from open spatial databases such as OSM (Bakillah et al., 2014).

Dasymetric mapping, combined with VGI, from the populR package (Batsaris & Kavroudakis, 2023) in r, is used to effectively transform block-level census population (night population) into finer spatial scales, and to capture population dynamics throughout the day (day population). Implementations of the *populR* package have been reported in Batsaris et al. (2023) and Batsaris & Kavroudakis (2023). These studies compare populR to other areal interpolation methods, highlighting its advantages. In this paper, the Float Dasymetric Interpolation (FDI) approach was employed, as it uses OSM VGI as ancillary information to transform population into a finer scale and capture fluctuations throughout the day.

Given a set of block-level polygons (s - source) along with population values (v) to interpolate, a set of building units (t - target) along with their number of floors (n) as additional information, and anOSM POI dataset, FDI interpolates population values as follows (Figure 5). First, the occupancy rate (r) is calculated for each building, which is an indicator of its probability of being inhabited at different times, such as night or day. This involves counting OSM points over buildings, adjusted by the number of floors, to estimate daytime occupancy rate (r_{tsd} – Eq. 1). Subsequently, this figure is further adjusted in order to measure the residential occupancy rate (r_{tsn} – Eq. 2). Next, FDI quantifies the relative share of each building (t) in the total effective area of all buildings within the block (s), considering the building footprint (a_{ts}), number of floors (n_{ts}), and occupancy rate (r_{tsx}) (Eq. 3). Finally, these weights (w_{ts}), when multiplied by the block population values (v_s) result in the population estimates of each building (p_{ts} – Eq. 4).

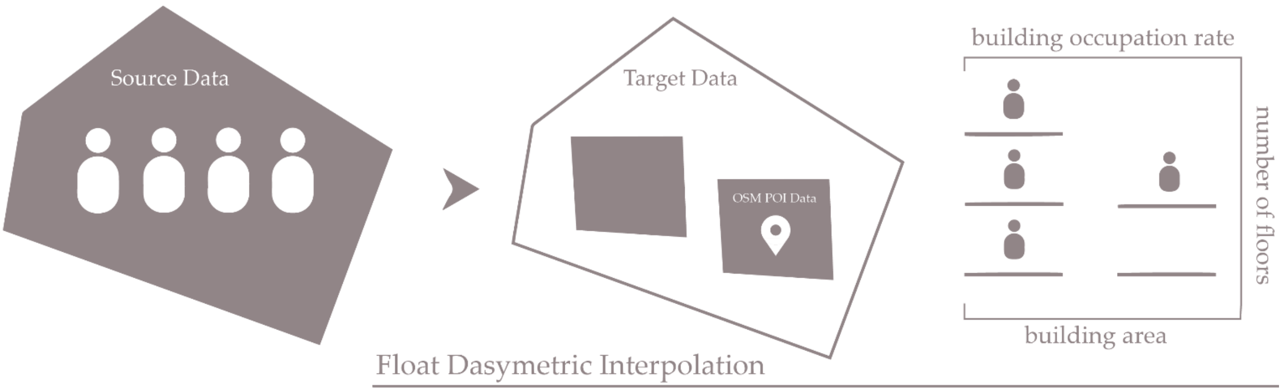


Figure 5. Float Dasymetric Interpolation flowchart

$$r_{tsd} = \frac{c_{ts}}{n_{ts}} \tag{1}$$

$$r_{tsn} = 1 - r_{tsd} \tag{2}$$

$$w_{ts} = \frac{a_{ts} \times n_{ts} \times r_{ts}}{\sum_{t \in s}(a_{ts} \times n_{ts} \times r_{tsx})} \tag{3}$$

$$p_{ts} = w_{ts} \times v_s \tag{4}$$

Where:
r_{tsx}: occupancy rate (day of night) of building *t* in block *s*
r_{tsd}: daytime occupancy rate of building *t* belongs to block, *s* during daytime
r_{tsn}: nighttime occupancy rate of building *t* belongs to block, *s* during nighttime
c_{ts}: count of VGI points over building *t* belongs to block *s*
w_{ts}: volume weight of building *t* belongs to block *s*
a_{ts}: area of building *t* belongs to block *s*
n_{ts}: number of floors of building *t* belongs to block *s*
p_{ts}: estimated population of building *t* belongs to block *s*
v_s: population of block *s*

The above equations have been implemented as user-friendly R functions provided by the *populR* package. A short demonstration using built-in package data is shown in the code block below. In the first line, the package is installed through the CRAN repository, attached to the script, and the source and target built-in data are loaded. OSM POI may be downloaded through the *pp_vgi* function by providing a valid spatial dataset in *simple format (sf)* and the desirable OSM tags to download. Next, the occupation ratio can be measured using the *pp_ancillary* function,

https://doi.org/10.48088/ejg.m.bat.16.2.052.065

and finally, population estimation is carried out by the main *pp_estimate* function. Input arguments include the target and source data, the id and population values of the source data, the target occupation ratio and the desired method (fdi).

```
# CRAN installation

install.packages("popuLR")

# attach package

library(popuLR)

# load built-in data

data('src')
     data('trg')

     # OSM POI

     trg <- pp_vgi(trg, key = c('amenity', 'clothes', 'healthcare', 'leisure',
           'military', 'office', 'religion', 'shop', 'social_facility, 'tourism'))

     # occupation ratio

     trg <- pp_ancillary(trg, volume = floors, key = 'pp_vgi')

     # estimate population

     trg <- pp_estimate(target = trg, source = src, sid = sid, spop = pop, volume = floors,
           ancillary = float, method = fdi)
```

Most of the casualties following a destructive earthquake mainly occur because of urban infrastructure and building collapse (X. Zhao et al., 2017). Therefore, the population in both scenarios is either at the place of residence or the place of work. Additionally, in line with previous studies (Batista e Silva et al., 2020; Freire et al., 2011) the population was divided into five broad groups in terms of age range and associated activities during the daytime, as show in Table 1. Areal interpolation implementation carried out for each one of the population groups and finally, created a unified layer comprising the daytime population by summing the results.

Table 1. Population categories based on age-groups, composition for each scenario and associated activities (OSM-related features)

Name	Age group	Night (%)	Day (%)	OSM Tags	OSM Keys
Home stayers	0 – 4 and 65+	100	20	–	
School Students	5 – 19	0	15	amenity	school, kindergarten, music_school
University Students	20 – 24	0	7.5	amenity	university, college, library
Working Population	25 – 64	0	78.5	amenity, clothes, healthcare, leisure, military, office, religion, shop, social_facility, tourism	-

Home stayers are a broad group of people and their ages range from 0 to 4 years old and from 65 years and above. Home stayers are assumed to stay at home in both night and day scenarios. Next, school students are the second category and include individuals from 5 to 19 years old. Another distinct group of people are university students aged from 20 to 24 years old. Finally, the working population group, which is the largest, and consists people of ages from 25 to 64 years old and includes both workers, shoppers, and visitors/tourists. School and university students are associated with certain keys of the amenity class of OSM features such as school, kindergarten and music_school for students and university, college and library for university students as they attend classes and other educational activities during the day, while during the night they stay at home. Working population is relatively bigger during the day as a lot of visitors and tourists go to Mytilini to access public services and/or attractions. A smaller amount of the working population stays at home during the night.

2.3.2. Location-Allocation

Location-Allocation involves three main components: a) a set of facilities (shelters) to choose from, b) a set of customers to allocate, and c) a metric system where costs can be measured (Azarmand & Jami, 2009; ReVelle & Eiselt, 2005). In the context of earthquake location-allocation,

https://doi.org/10.48088/ejg.m.bat.16.2.052.065

these data include a set of alternative facilities with finite capacity available for selection (shelters), a set of customers with known demand (population counts), and a metric system to calculate costs (road network). In earthquake shelter selection applications, accessibility is of significant importance. Main measures of accessibility include travel time or travel distance between pairs of origins and destinations. GIS provides a comprehensive toolset to store, access, process, and visualize spatial data and complex spatial structures.

ArcGIS is an off-the-shelf GIS software that provides a Network Analysis tool for addressing several location analysis problems including location-allocation (Jiao & Feng, 2024). The location-allocation layer provides a wide range of methods using different objectives and constraints. Maximize Capacitated Coverage is well-suited in the present case study in which earthquake shelters can only serve a limited number of people and simultaneously shelters must be accessible in reasonable distance by the population. The goal of Maximize Capacitated Coverage method is to identify facilities that can serve as much as possible demand points within a certain distance (maximize coverage). If the distance parameter is missing, then it behaves like the classic p-median approach where the objective is to minimize traveling costs. To solve this problem, first, an origin-destination (OD) cost matrix is created using Dijkstra's shortest path algorithm (Dijkstra, 1959) and edited using Hillsman calibration method. Then, a group of good semi-random solutions is created to feed a metaheuristic for further optimization. The solver stops if no additional improvement is possible and returns the best solution found. The combination of all of the above yields near-optimal results (Network Analyst Extension, 2024a, 2024b).

3. Results

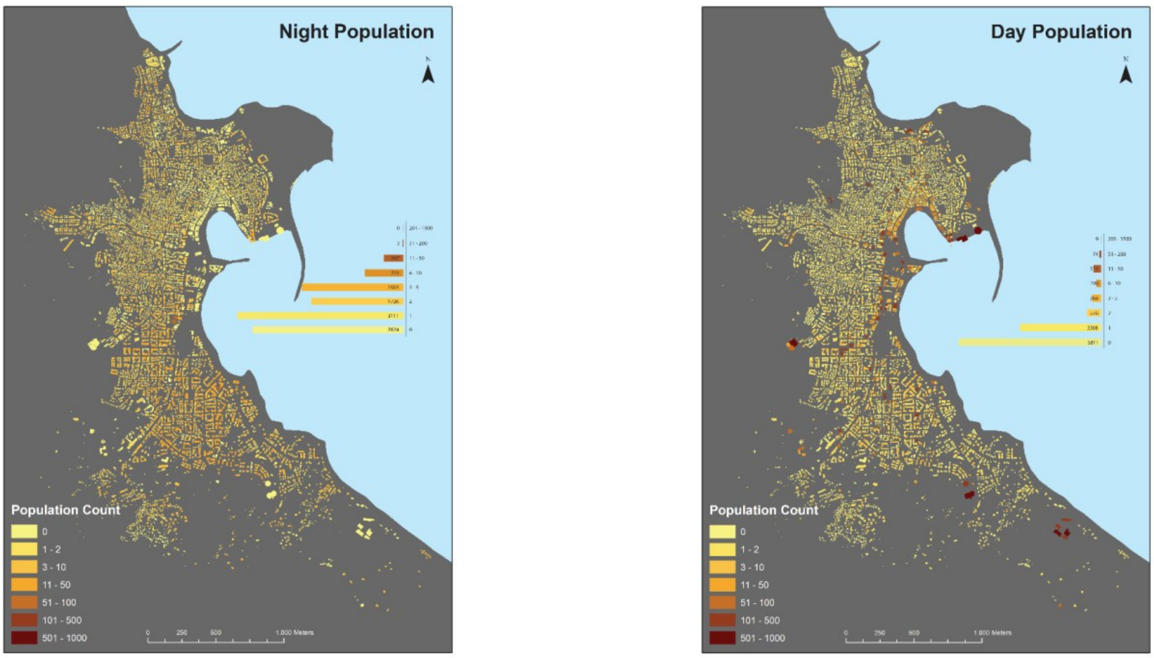
The aim of this paper, is to underscore the importance of population dynamics in the context of earthquake shelter location-allocation. Primarily, it is important to determine the location of the population when a destructive earthquake may occur. For this purpose, census population data were transformed into a finer scale, and population distribution during the daytime was also estimated, using areal interpolation methods and VGI as ancillary information. Finally, the results of the spatial and temporal refinements of census population were used to explore their influence on the location-allocation analysis, with the city Mytilini serving as the case study.

3.1 Population Dynamics Using Areal Interpolation

Ancillary information retrieved by OSM is crucial to the process of areal interpolation of the population as it highlights potential clusters of population concentration at different times of the day. The vast majority of OSM points appear in the coastal zone, whereas only a few are found in the eastern and southern parts of the city, which mainly include educational infrastructure and small businesses. The proposed method for spatial and temporal refinement of the population uses areal weights multiplied by the number of floors and occupancy rate for each building. As a result, high-rise buildings with large footprints and more POIs are more likely to attract more population than smaller ones.

The outcomes of the night scenario are depicted in Figure 6a. Significant population concentrations appear in the southern part of Mytilene, where buildings are somehow bigger and fewer OSM data are noted. Conversely, the central and northern parts of the city, where buildings are relatively smaller and represent a mix of residential and commercial zone, the population concentration is significantly lower.

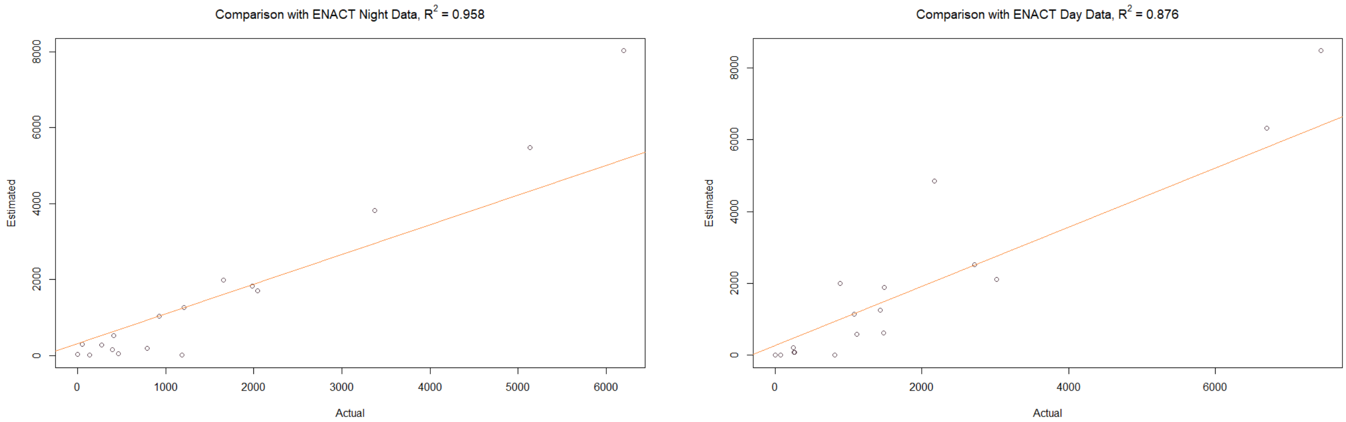
A significant shift in terms of population concentration towards mixed and commercial zones, is observed in the day scenario (Figure 6b). Groups such as University and school students, which during the morning hours attend classes, are concentrated in educational facilities (schools, universities and libraries). The working population is mainly concentrated in the coastal zone, city center, and around the port of the city, where most of the businesses are. Finally, the rest of the population (home stayers) stay at home.



a b

Figure 6. Population spatial refinement and temporal estimation. a) night scenario – residential- population, and b) day scenario – population during the daytime

Population outcomes were further evaluated using the results of the ENhancing ACTivity and population mapping (ENACT) project (Batista e Silva et al., 2020) of the JRC of the European Commission. Figure 7 compares each scenario with the corresponding ENACT data. Each point in the scatterplot represents a data observation, with the x-axis showing the actual population values and the y-axis the estimated values. The orange line represents the fitted linear regression model, and its slope reflects the proportional relationship between actual and estimated values. In both cases, our approach underestimates population in comparison to ENACT as the slope of the regression line falls below the $y = x$ diagonal, especially for larger actual values in the night scenario. Despite this bias, the correlation coefficient R^2 is high in both night and day scenarios, demonstrating the effectiveness of the FDI approach.



a b

Figure 7. Evaluation of the results acquired by the *populR* package and those retrieved by the ENACT project of the JRC (Joint Research Centre). a) scatterplot of the night dataset and b) scatterplot of the day datasets

Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) were also measured and are presented in Table 2. The error metrics reveal the performance of the FDI approach when compared to ENACT data. FDI performs very well in capturing population at night, explaining 95,8% of the variance in the actual values, with relatively low errors per square kilometer (RMSE 594.17 and MAE 387.06). In contrast, for the day scenario, lower R^2 and higher error metrics indicate a decrease in FDI's ability to capture daytime population distribution compared to ENACT population. Capturing population dynamics during the day is a challenging task; however, the FDI approach performs adequately in both scenarios.

Table 2. Error measurements and R^2 of the population outcomes in comparison with ENACT project.

Name	**RMSE**	**MAE**	**R^2**
Night vs ENACT	594.17	387.06	0.958
Day vs ENACT	854.23	566.53	0.876

3.2 Location-Allocation

In this subsection, location-allocation analysis is carried out to examine the importance of population dynamics. Three location-allocation scenarios are produced: Block Allocations (using block-level census population data), Night Allocations (using building-level residential population), and Daytime Allocations (using building-level daytime population distribution estimation). To explore the impact of granularity on location-allocation outcomes, a comparison of Block and Night allocations was undertaken. Next, a comparison between Day and Night Allocations was carried out to investigate the influence of population dynamics in the context of shelter selection and population allocation.

3.2.1 Comparison of block and night allocations

Figure 8 visually compares the results as spider maps. Orange markers indicate the selected locations, while red marks indicate unselected locations. Green lines represent the allocation lines for each building unit. In the first scenario (Figure 8a), the population is concentrated in the center of city blocks (centroid), which is a generalization, and may lead to less accurate results. In contrast, the second scenario Figure 8b) uses the granularity of individual buildings (Figure 8b), where the distribution of the population is more detailed. As a result, distances are measured with higher accuracy and therefore, provides more realistic outcomes.

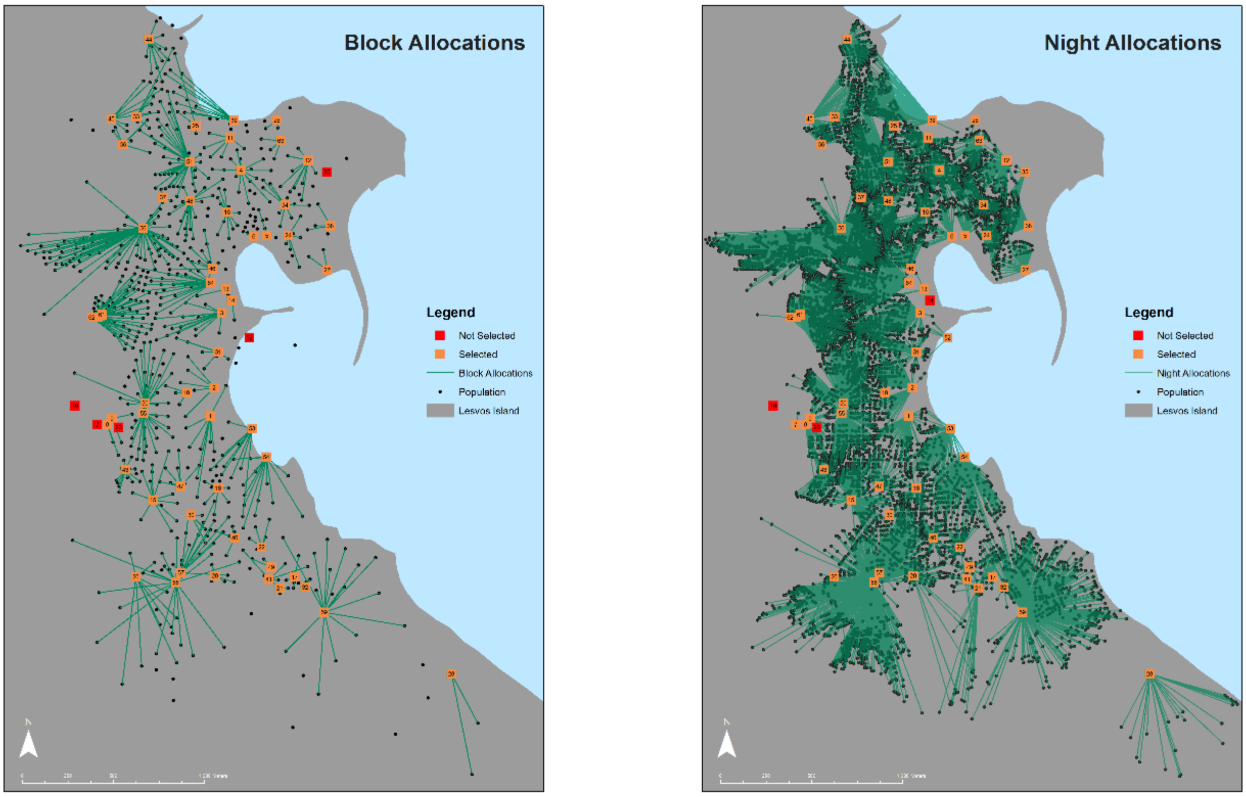
The results indicate differences in shelter location selection. In both cases, there are a few locations that are not serving the population in an optimal way and were not selected by the ArcGIS location-allocation solver. Particularly, in the block scenario, there are five shelters, while on

https://doi.org/10.48088/ejg.m.bat.16.2.052.065

the night scenario (building scenario) there are only three. Additionally, in terms of allocations, a notable difference of 450000 meters in total walking distances and 25 meters in mean walking distances observed as shown in Table 3.

Table 3. Comparison of total and mean distance, and selected locations between block and night scenarios

Name	Total Distance (m)	Mean Distance (m)	Locations
Block	7467863	291	59
Night	6892261	268	61



a b

Figure 8. Visual comparison of location-allocation results. a) using block-level census data – block allocations, and b) spatially refined building-level population – night allocations

Figure 9 depicts the comparisons of capacities between the two scenarios and the actual shelter capacities. There are notable differences between the two scenarios. In the block scenario, where population is concentrated in 556 city blocks, larger cohorts of population are assigned to the closest shelter which affects the location-allocation process especially in cases where the closest shelters are nearly full. In greater detail, in the block scenario there are 5 shelters which were not selected, and another 5 in which less than 5% of their capacity is used. There are 3 spaces used 100% of their capacity and another 25 which are near-full. In contrast, the picture is slightly different using detailed population data, where there are only 3 spaces using less than 5% of their capacity and 28 fully utilized.

3.2.2 Comparison of night and day allocations

In the night allocation scenario, the population stays at home while during the day population moves towards their activities. As a result, university and school students attend classes and walk very short distances as school courts, yards and university campuses are shelters themselves. Fewer people stay at home during the daytime and finally, the majority of the population is at their workplaces, which are primarily along the coastline and around the port of Mytilene, where shelters tend to be relatively smaller. A visual comparison of the two scenarios is depicted in Figure 10.

Population distribution patterns between the two scenarios provide insights regarding the areas with increased demand for sheltering. In deeper analysis, high-demand areas shift from residential zones at night to mixed and commercial zones during the day which affects both shelter location and allocation decisions. As a result, the total walking distance is higher in the Niight Allocation scenario (more than 872,000 meters) in comparison

https://doi.org/10.48088/ejg.m.bat.16.2.052.065

to the Day Allocation scenario, as shown in Table 4. Furthermore, the outcomes highlight that during the day more shelters are selected due to population shifts towards their activities.

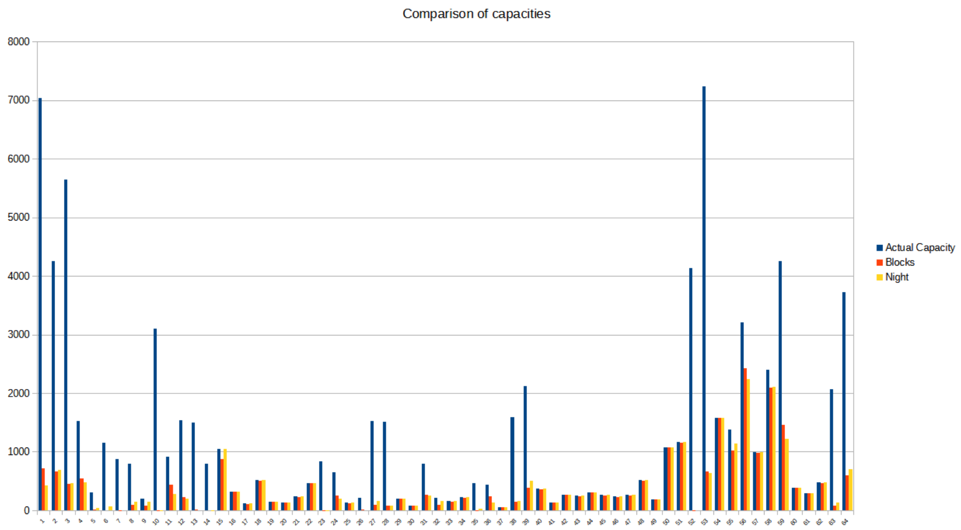
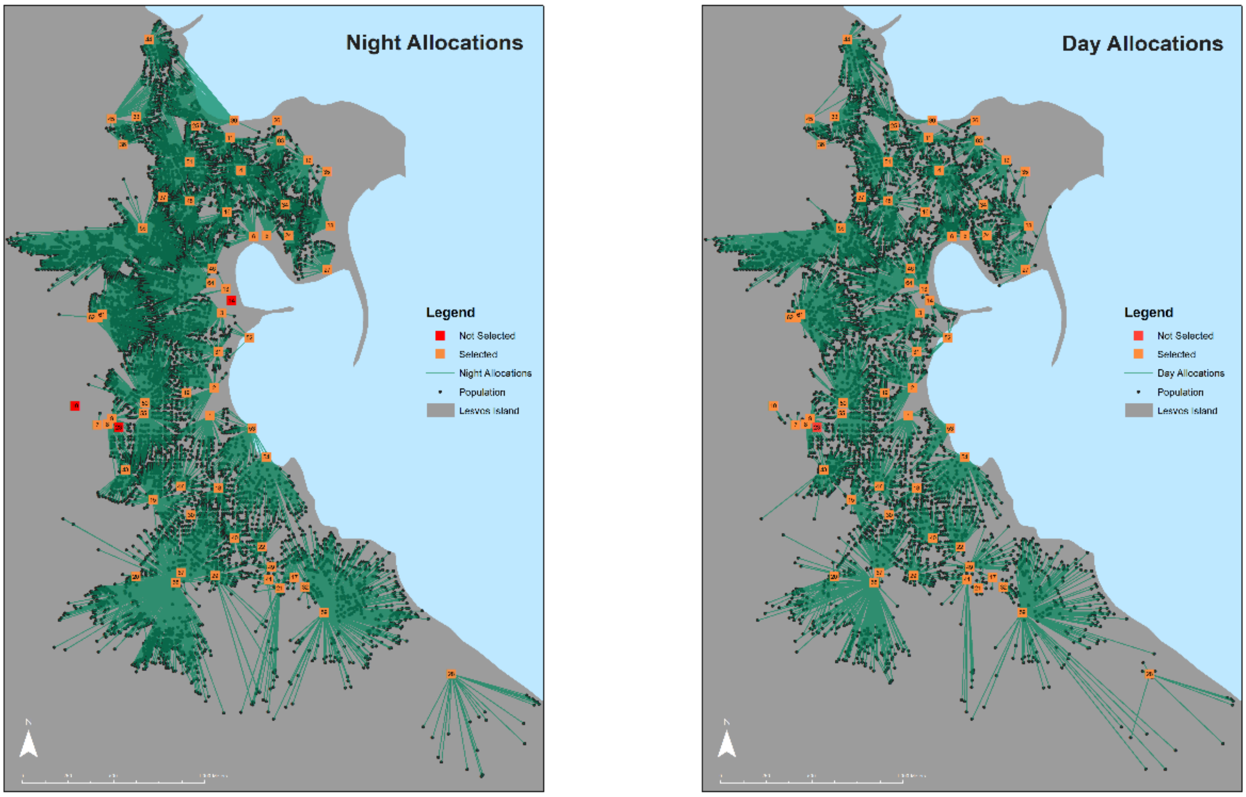


Figure 9. Comparison of the actual capacities (blue) and the capacities retrieved by the block allocations scenario (red) and night allocations scenario (yellow).

Comparisons between actual capacities and the night and day scenarios are presented in Figure 11. A closer look into the figure reveals significant differences in terms of shelter needs for more than ten shelters. There are more than 10 shelters in which evacuation demand is higher during the day than at night, as a result of population fluctuations. In the daytime scenario, 17 shelters are operating at full capacity, while another 7 are nearly full. There are also 7 shelters that use less than 5% of their capacity from which two of them serve a total of 6 individuals.



a b

Figure 10. Visual comparison between Night and Day location-allocation scenarios. a) building-level Night Allocations and b) building-level Day Allocations.

Table 4. Comparisons of total and mean distances, and selected locations in night and day scenarios

Name	Total Distance (m)	Mean Distance (m)	Locations
Night	6892261	268	61
Day	6020011	234	63

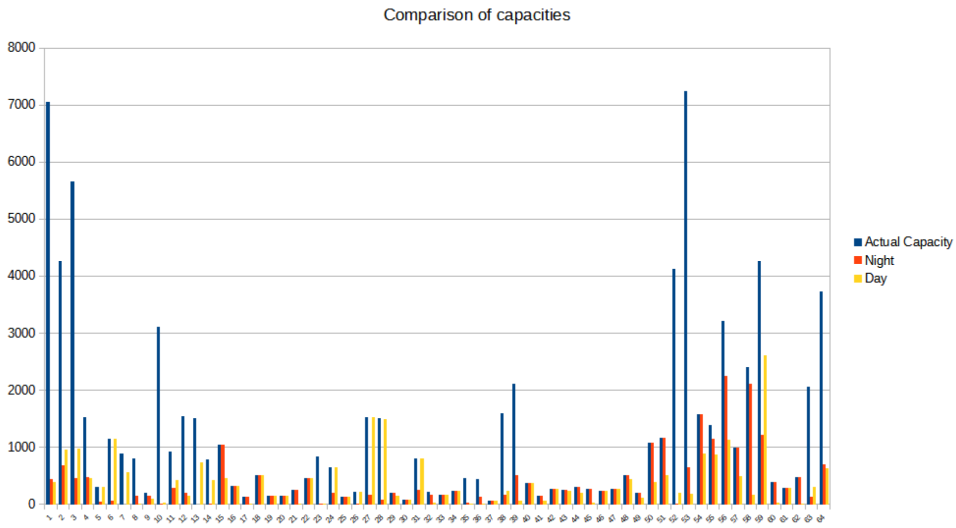


Figure 11. Comparison of the actual capacities (blue) and the capacities retrieved by the Night allocations scenario (red) and Day allocations scenario (yellow).

4. Discussion

In this study, the significance of incorporating population dynamics into the location-allocation analysis of earthquake evacuation shelters, using the city of Mytilini as the case study, is examined. The results demonstrated that spatio-temporal population refinements influence the outcomes of shelter planning, with implications for improving evacuation strategies and ensuring resource optimization.

Refinements of census data revealed differences in population distribution between the night and day scenarios. Night population mainly concentrates in residential areas, where larger buildings and fewer OSM data exist, while during the day concentrations shifted towards mixed and commercial zones. Comparisons to ENACT data validated the effectiveness of the proposed areal interpolation implementation, particularly for the night scenario. However, the proposed approach was less effective in estimating daytime population reflecting the challenges of capturing daytime patterns of mobility. Despite its strong performance, the proposed method has two important limitations that must be acknowledged. One key limitation is the reliance in census data, which are not fully account for tourists and visitors, potentially leading to underestimation in specific zones, especially during the daytime. OSM data, serves as a valuable source of information for areal interpolation; however, its use comes with challenges that must be addressed. Although OSM data is reviewed before publication, its quantity, accuracy and quality largely depend on the experience and contribution of volunteers, the available tools and different techniques which can vary significantly between locations (Bakillah et al., 2014). Another notable limitation is the lack of systematic updates, which means that recent changes may not always be captured (Batsaris et al., 2023). For example, in this study, intersecting OSM data included approximately 1300 businesses, private and public organizations – representing only about a 37% of the actual number reported by the Chamber of Lesvos for the year of 2024. Improvements, of the proposed method may be achieved by utilizing additional sources of data such as LUCAS points (Gallego, 2010) and social media data (Sinnott & Wang, 2017) to address population dynamics during the daytime.

Location-allocation analysis also provided valuable insights into how the granularity and temporal dynamics of population impact earthquake shelter planning. Building-level data achieved less total walking distances, better shelter selection and capacity management in comparison to block-level census data, due to the generalization of population representation in block centroids. The comparison of night and day allocations highlighted a significant shift in evacuation demand which showcases the importance of incorporating population dynamics for better location selection to avoid overcrowding and/or shelter underutilization and efficient allocations to minimize the walking distances to shelters as well as, to achieve better capacity management.

The findings of this study have practical implications for earthquake shelter planning. Using static census data may lead to less efficient results, while incorporating spatio-temporal refinements of population data can optimize shelter location and utilization as well as more efficient allocations. Insights about population distribution patterns under different scenarios, can assist planners in making more informed decisions about shelter placement, ensure better accessibility, and avoid overcrowding or underutilization of the available resources. Moreover, the observed shift in evacuation demand between night and day underscores the need for adaptive evacuation strategies that address these dynamic shifts. Planners should consider flexible approaches to enhance disaster preparedness and community resilience, especially in urban environments with significant daytime mobility.

https://doi.org/10.48088/ejg.m.bat.16.2.052.065

5. Conclusions

Location-allocation has been extensively used for shelter placement and allocation of the population in disaster-related applications. Most of the existing approaches rely on static commune-level residential population data, often neglecting the dynamics of population mobility. This may lead to sub-optimal shelter placement and inefficient allocations. In this study, the influence of spatial and temporal refinements of the census population is examined in the context of location-allocation analysis.

The study contributes to the continuously growing location-allocation literature as follows:

1. Refined spatial and temporal population estimations for emergency planning: In this paper, areal interpolation methods were utilized along with open spatial information to enhance the spatial and temporal granularity of census data. Accurate representations of population distribution throughout the day are crucial for efficient earthquake emergency planning and show significant changes in population distribution patterns between day and night.
2. Influence of population dynamics on earthquake shelter location-allocation: Detailed spatio-temporal population distribution data were used in location-allocation analysis to determine how they influence the process of shelter selection and allocation of affected populations. The findings of the study demonstrate that refined spatio-temporal population data may lead to more efficient shelter selection and better accessibility and, highlight the importance of integrating population dynamics into shaping disaster preparedness plans.

To examine the efficiency of the proposed methods, actual data from the city of Mytilini, Lesvos, Greece, were used. Initially, building-level population refinements were estimated for day and night and then used in the context of location-allocation analysis. Three location-allocation scenarios were examined including the direct use of census block-level population data (block allocations), a building-level night scenario (night allocations), and a building-level day scenario (day allocations). We first showed the advantages of using detailed population data by comparing the block allocations with night allocations. Then, we provided comparisons between building-level night and day location-allocation scenarios to highlight the influence of using population dynamics in location-allocation analysis.

The outcomes of this study provide improved results when comparing block and night allocation scenarios. In addition, estimation of population distribution during the day provides better information about optimal shelter placement, and efficient capacity management as well as their impact on population allocation. Incorporating population dynamics into emergency shelter location-allocation analysis will enhance earthquake resilience, support emergency planners in improving disaster preparedness, and increase shelter accessibility in the aftermath of earthquakes.

Funding: This research received no external funding.

Data Availability Statement: Data is available on request. Please contact the corresponding author.

Conflicts of Interest: The author declares no conflict of interest.

References

Anhorn, J., & Khazai, B. (2015). Open space suitability analysis for emergency shelter after an earthquake. *Natural Hazards and Earth System Sciences*, *15*(4), 789–803. https://doi.org/10.5194/nhess-15-789-2015

Azarmand, Z., & Jami, E. N. (2009). *Location Allocation Problem*. *2001*, 19–36. https://doi.org/10.1007/978-3-7908-2151-2

Bakillah, M., Liang, S., Mobasheri, A., Jokar Arsanjani, J., & Zipf, A. (2014). Fine-resolution population mapping using OpenStreetMap points-of-interest. *International Journal of Geographical Information Science*, *28*(9), 1940–1963. https://doi.org/10.1080/13658816.2014.909045

Bao, W., Gong, A., Zhang, T., Zhao, Y., Li, B., & Chen, S. (2023). Mapping Population Distribution with High Spatiotemporal Resolution in Beijing Using Baidu Heat Map Data. *Remote Sensing*, *15*(2), 1–22. https://doi.org/10.3390/rs15020458

Batista e Silva, F., Freire, S., Schiavina, M., Rosina, K., Marín-Herrera, M. A., Ziemba, L., Craglia, M., Koomen, E., & Lavalle, C. (2020). Uncovering temporal changes in Europe's population density patterns using a data fusion approach. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-18344-5

Batsaris, M., & Kavroudakis, D. (2023). populR: an R Package for Population Downscaling. *The R Journal*, *14*(December), 223–234. https://doi.org/https://doi.org/10.32614/RJ-2023-007

Batsaris, M., Kavroudakis, D., Soulakellis, N. A., & Kontos, T. (2019). Location-Allocation Modeling for Emergency Evacuation Planning in a Smart City Context. *International Journal of Applied Geospatial Research*, *10*(4), 28–43. https://doi.org/10.4018/ijagr.2019100103

Batsaris, M., Zafeirelli, S., Vaitis, M., & Kavroudakis, D. (2023). PoD: A Web Tool for Population Downscaling Using Areal Interpolation and Volunteered Geographic Information. *European Journal of Geography*, *14*(4), 22–36. https://doi.org/10.48088/EJG.M.BAT.14.4.022.036

Bergroth, C., Järv, O., Tenkanen, H., Manninen, M., & Toivonen, T. (2022). A 24-hour population distribution dataset based on mobile phone data from Helsinki Metropolitan Area, Finland. *Scientific Data*, *9*(1), 1–19. https://doi.org/10.1038/s41597-021-01113-4

Bhaduri, B., Bright, E., Coleman, P., & Urban, M. L. (2007). LandScan USA: A high-resolution geospatial and temporal modeling approach for population distribution and dynamics. *GeoJournal*, *69*(1–2), 103–117. https://doi.org/10.1007/s10708-007-9105-9

Bian, R., & Wilmot, C. G. (2015). Spatiotemporal Population Distribution Method for Emergency Evacuation. *Transportation Research Record: Journal of the Transportation Research Board*, *2532*(1), 99–106. https://doi.org/10.3141/2532-12

Chaidas, K., Tataris, G., & Soulakellis, N. (2021). Seismic damage semantics on post-earthquake lod3 building models generated by uas. *ISPRS International Journal of Geo-Information*, *10*(5). https://doi.org/10.3390/ijgi10050345

Chang, K. H., Pan, Y. J., & Chen, H. (2024). Shelter location–allocation problem for disaster evacuation planning: A simulation optimization approach. *Computers and Operations Research*, *171*(September 2023), 106784. https://doi.org/10.1016/j.cor.2024.106784

Chen, Z., Chen, X., Li, Q., & Chen, J. (2013). The temporal hierarchy of shelters: a hierarchical location model for earthquake-shelter planning. *International Journal of Geographical Information Science*, *27*(8), 1612–1630. https://doi.org/10.1080/13658816.2013.763944

Comber, A., & Zeng, W. (2019). Spatial interpolation using areal features: A review of methods and opportunities using new forms of data with coded illustrations. *Geography Compass*, *13*(10), 1–23. https://doi.org/10.1111/gec3.12465

Dehnavi Eelagh, M., & Ali Abbaspour, R. (2024). A location-allocation optimization model for post-earthquake emergency shelters using network-based multi-criteria decision-making. *Decision Analytics Journal*, *10*(February), 100430. https://doi.org/10.1016/j.dajour.2024.100430

Dijkstra, E. W. (1959). A note on two problems in connection with graphs. *Numerische Mathematik*, *1*(1), 269–271. https://doi.org/10.1007/BF01386390

Freire, S., & Aubrecht, C. (2012a). Integrating population dynamics into mapping human exposure to seismic hazard. *Natural Hazards and Earth System Science*, *12*(11), 3533–3543. https://doi.org/10.5194/nhess-12-3533-2012

Freire, S., & Aubrecht, C. (2012b). Integrating population dynamics into mapping human exposure to seismic hazard. *Natural Hazards and Earth System Science*, *12*(11), 3533–3543. https://doi.org/10.5194/nhess-12-3533-2012

Freire, S., Aubrecht, C., & Wegscheider, S. (2011). Spatio-temporal population distribution and evacuation modeling for improving tsunami risk assessment in the Lisbon Metropolitan Area. *Geo-Information for Disaster Management (Gi4DM)*, *May*, 1–6. http://elib.dlr.de/74594/1/OP32.pdf

Gallego, F. J. (2010). A population density grid of the European Union. *Population and Environment*, *31*(6), 460–473. https://doi.org/10.1007/s11111-010-0108-y

Geng, S., Hou, H., & Zhou, Z. (2021). A hybrid approach of vikor and bi-objective decision model for emergency shelter location–allocation to respond to earthquakes. *Mathematics*, *9*(16). https://doi.org/10.3390/math9161897

Hellenic Statistical Authority. (2009). *2001 Population and Housing Census of Greece*.

Hellenic Statistical Authority. (2014). *2011 Population and Housing Census of Greece* (Issue April). https://www.statistics.gr/en/2011-census-pop-hous

Hu, F., Xu, W., & Li, X. (2012). A modified particle swarm optimization algorithm for optimal allocation of earthquake emergency shelters. *International Journal of Geographical Information Science*, *26*(9), 1643–1666. https://doi.org/10.1080/13658816.2011.643802

Jiao, H., & Feng, S. (2024). Towards Resilient Cities: Optimizing Shelter Site Selection and Disaster Prevention Life Circle Construction Using GIS and Supply-Demand Considerations. *Sustainability*, *16*(6), 2345. https://doi.org/10.3390/su16062345

Kaveh, A., Javadi, S. M., & Moghanni, R. M. (2020). Emergency management systems after disastrous earthquakes using optimization methods: A comprehensive review. *Advances in Engineering Software*, *149*(March), 102885. https://doi.org/10.1016/j.advengsoft.2020.102885

Kilci, F., Kara, B. Y., & Bozkaya, B. (2015). Locating temporary shelter areas after an earthquake: A case for Turkey. *European Journal of Operational Research*, *243*(1), 323–332. https://doi.org/10.1016/j.ejor.2014.11.035

Lam, N. S. N. (1983). Spatial interpolation methods: A review. *The American Cartographer*, *10*(2), 129–150. https://doi.org/10.1559/152304083783914958

Ma, Y., Xu, W., Qin, L., & Zhao, X. (2019). Site selection models in natural disaster shelters: A review. *Sustainability (Switzerland)*, *11*(2), 1–24. https://doi.org/10.3390/su11020399

Mennis, J. (2003). Generating Surface Models of Population Using Dasymetric Mapping*. *The Professional Geographer*, *55*(1), 31–42. https://doi.org/10.1111/0033-0124.10042

Mennis, J. (2016). Dasymetric Spatiotemporal Interpolation. *Professional Geographer*, *68*(1), 92–102. https://doi.org/10.1080/00330124.2015.1033669

Network Analyst Extension, A. (2024a). *Algorithms used by the ArcGIS Network Analyst extension*. https://desktop.arcgis.com/en/arcmap/10.5/extensions/network-analyst/algorithms-used-by-network-analyst.htm#GUID-D50336EC-7FBA-43FA-AD31-4272AB544393

Network Analyst Extension, A. (2024b). *Location-allocation analysis*. https://desktop.arcgis.com/en/arcmap/10.5/extensions/network-analyst/location-allocation.htm

Padgham, M., Lovelace, R., Salmon, M., & Rudis, B. (2017). Osmdata. *The Journal of Open Source Software*, *2*(14), 305. https://doi.org/10.21105/joss.00305

Pebesma, E. (2018). Simple features for R: Standardized support for spatial vector data. *R Journal*, *10*(1), 439–446. https://doi.org/10.32614/rj-2018-009

R Core Team. (2015). *R: a Language and Environment for Statistical Computing.* http://www.r-project.org/

ReVelle, C. S., & Eiselt, H. A. (2005). Location analysis: A synthesis and survey. *European Journal of Operational Research*, *165*(1), 1–19. https://doi.org/10.1016/j.ejor.2003.11.032

Scott, A. J. (1970). Location-Allocation Systems: A Review. *Geographical Analysis*, *2*(2), 95–119. https://doi.org/10.1111/j.1538-4632.1970.tb00149.x

Sinnott, R. O., & Wang, W. (2017). Estimating micro-populations through social media analytics. *Social Network Analysis and Mining*, *7*(1). https://doi.org/10.1007/s13278-017-0433-6

Tang, K., & Osaragi, T. (2024). Multi-Objective Distributionally Robust Optimization for Earthquake Shelter Planning Under Demand Uncertainties. *GeoHazards*, *5*(4), 1308–1325. https://doi.org/10.3390/geohazards5040062

Tenerelli, P., Gallego, J. F., & Ehrlich, D. (2015). Population density modelling in support of disaster risk assessment. *International Journal of Disaster Risk Reduction*, *13*, 334–341. https://doi.org/10.1016/j.ijdrr.2015.07.015

Wang, W., Wu, S., Wang, S., Zhen, L., & Qu, X. (2021). Emergency facility location problems in logistics: Status and perspectives. *Transportation Research Part E: Logistics and Transportation Review*, *154*(August), 102465. https://doi.org/10.1016/j.tre.2021.102465

Wu, S., Qiu, X., & Wang, L. (2005). Population Estimation Methods in GIS and Remote Sensing: A Review. *GIScience & Remote Sensing*, *42*(1), 80–96. https://doi.org/10.2747/1548-1603.42.1.80

Xu, J., Yin, X., Chen, D., An, J., & Nie, G. (2016). Multi-criteria location model of earthquake evacuation shelters to aid in urban planning. *International Journal of Disaster Risk Reduction*, *20*(October), 51–62. https://doi.org/10.1016/j.ijdrr.2016.10.009

Xu, W., Ma, Y., Zhao, X., Li, Y., Qin, L., & Du, J. (2018). A comparison of scenario-based hybrid bilevel and multi-objective location-allocation models for earthquake emergency shelters: A case study in the central area of Beijing, China. *International Journal of Geographical Information Science*, *32*(2), 236–256. https://doi.org/10.1080/13658816.2017.1395882

Ye, M., Wang, J., Huang, J., Xu, S., & Chen, Z. (2012). Methodology and its application for community-scale evacuation planning against earthquake disaster. *Natural Hazards*, *61*(3), 881–892. https://doi.org/10.1007/s11069-011-9803-y

Younes, A., Ahmad, A., Hanjagi, A. D., & Nair, A. M. (2023). Understanding Dynamics of Land Use & Land Cover Change Using GIS & Change Detection Techniques in Tartous , Syria. *European Journal of Geography*, *14*(3), 20–41. https://doi.org/10.48088/ejg.a.you.14.3.020.041

Zhang, X., Yu, J., Chen, Y., Wen, J., Chen, J., & Yin, Z. (2020). Supply–Demand Analysis of Urban Emergency Shelters Based on Spatiotemporal Population Estimation. *International Journal of Disaster Risk Science*, *11*(4), 519–537. https://doi.org/10.1007/s13753-020-00284-9

Zhao, L., Li, H., Sun, Y., Huang, R., Hu, Q., Wang, J., & Gao, F. (2017). Planning emergency shelters for urban disaster resilience: An integrated location-allocation modeling approach. *Sustainability (Switzerland)*, *9*(11), 1–20. https://doi.org/10.3390/su9112098

Zhao, X., Coates, G., & Xu, W. (2017). Solving the earthquake disaster shelter location-allocation problem using optimization heuristics. *14th ISCRAM Conference*, *May*, 50–62.

Zhao, X., Xu, W., Ma, Y., & Hu, F. (2015). Scenario-based multi-objective optimum allocation model for earthquake emergency shelters using a modified particle swarm optimization algorithm: A case study in Chaoyang District, Beijing, China. *PLoS ONE*, *10*(12), 1–16. https://doi.org/10.1371/journal.pone.0144455

Zouros, N., Pavlides, S., Soulakellis, N., Chatzipetros, A., Vasileiadou, K., Valiakos, I., & Mpentana, K. (2011). Using active fault studies for raising public awareness and sensitisation on seismic hazard: A case study from Lesvos petrified forest Geopark, NE Aegean sea, Greece. *Geoheritage*, *3*(4), 317–327. https://doi.org/10.1007/s12371-011-0044-y

European Journal of Geography