IJIO
(*International Journal of Industrial Optimization*)
ISSN 2723-3022 (online) | 2714-6006 (printed)
Vol 6, No. 2, 124-146
https://doi.org/10.12928/ijio.v6i2.11406

A simulation framework for emergency evacuation, considering navigation errors

Oren E. Nahum [a,*], Omri Mayost [b]

[a] Department of Economics and Logistics, Faculty of Economics, Ashkelon Academic College, Israel
[b] Department of Management, Faculty of Social Sciences, Bar-Ilan University, Israel
* Corresponding Author: oren.e.nahum@gmail.com

ARTICLE INFO

Article history
Received: August 20, 2024
Revised: January 11, 2025
Accepted: April 29, 2025

Keywords
Tourism industry;
Simulation;
Evacuation;
Navigation errors;
MATSim.

ABSTRACT

The rapidly growing tourism industry has brought forth substantial safety concerns, particularly in the context of emergency evacuations necessitated by natural and human-induced disasters. Tourists often lack the necessary orientation, information, and preparedness, rendering them vulnerable during such crises. While research has extensively explored tourist behavior and evacuation procedures independently, the intersection of these two fields remains underexamined. This study introduces a simulation model utilizing MATSim to characterize the behaviors of tourists during emergencies, highlighting navigation errors and decision-making processes. Two novel routers - "Random Walk" and "Landmark Assisted" - have been developed to better reflect tourist navigation challenges. A case study in Conegliano, Italy, demonstrates the effectiveness of these routers under two evacuation policies: predefined and undefined destinations. Results indicate significant disparities in evacuation times: optimal routes average 50 minutes, while random navigation extends this to 544 minutes. The Landmark Assisted router improves evacuation to 73 minutes, underscoring the importance of identifiable landmarks. Additionally, managing intersections further reduces evacuation times. This simulation framework serves as a decision-making tool for evaluating evacuation policies, providing insights into optimizing resource allocation and enhancing overall efficacy in emergency scenarios. Future research should focus on developing optimization algorithms for intersection management selection, reinforcing the practical applicability of this model in real-world contexts.

1. Introduction

The field of tourism represents one of the most rapidly expanding industries, thereby leading to an increase in related safety concerns triggered by both natural and human induced calamities. Armed conflict, terrorist attacks, tempests, seismic activities and volcanic eruptions necessitate the immediate and often chaotic relocation of people from the affected areas to designated disaster-free zones. Within these unpredictable and high-risk circumstances, tourists invariably find themselves at a distinct disadvantage due to a lack of orientation, information and preparedness. As a consequence, their propensity to fall victim to unsafe situations is considerably high [1].

The concept of tourist evacuation straddles two distinct fields of study: tourism and evacuation procedures. While each of these areas has been thoroughly investigated within its respective field, the intersection between the two - specifically the implementation of evacuation procedures within the context of tourism - remains largely unexplored in both theoretical research and practical application.

The primary focus of contemporary research into tourist evacuation is on understanding tourist behavior. This is often derived from surveys associated with specific occurrences such as hurricanes and tsunamis. For example, the study of Cahyanto and Pennington-Gray [2] amassed tourist responses to dissect factors such as role, gender, location of residence, and previous encounters with hurricanes with a focus on voluntary evacuation. Similarly, Drabek [3] conducted an assessment leveraging interviews to elucidate the differential responses between tourists and local population during disasters. This was aimed at guiding local authorities in formulating effective measures accordingly.

Evidence from numerous studies, including those by Goeldner-Gianella, et al. [4] and Matyas, et al. [5], suggests a significant difference in the behavior of tourists compared to residents. While this difference in behavior offers insightful information, it is vital to delve deeper to comprehend the movement patterns of these tourists. This understanding will contribute to identifying areas with a high concentration of evacuees, thereby facilitating the development of evacuation routes and suitable locations for shelters [6]–[10].

Extensive literature exists on residential flow pattern models, given their crucial role in transportation planning, more so in the approximation of origin-destination (OD) flows. Methods for data collection encompass surveys and various technological signals such as mobile phones, public transportation smart cards, loop detectors, and Bluetooth, among others [11]–[14].

Numerous investigations have scrutinized the process of evacuation optimization, incorporating an assortment of parameters. However, these studies often overlook the potential impact of diverse populations, such as tourists, on the overall evacuation. It is worth noting that disaster-prone areas often coincide with popular tourist destinations, thus the number of tourists present could have a noteworthy effect on the evacuation procedure. Tourists exhibit distinct characteristics in their emergency responses, largely attributed to unfamiliarity with the locale and potential language barriers.

The utilization of behavioral insights was pivotal to the assessment of tourist evacuation through the application of simulation models. Distinguished researchers such as Kinugasa and Nakatani [15], Kinugasa, et al. [16], and Emori, et al. [17] significantly contributed to this endeavor by establishing a tourist evacuation guidance support system - a specialized instrument designed to ascertain the efficacy of various guidance methodologies. Notably, this instrument contains a lacuna, namely, the absence of feedback sourced directly from tourists. Materializing this feedback can be executed through the deployment of inexpensive and energy-efficient miniature communication beacons, like Bluetooth and LoRa [18]–[21]. Such advanced devices can serve two crucial functions: notifying tourists if they veer off the prescribed evacuation trajectory and facilitating the technology required for managing intersections in a controlled manner.

In previous studies [22], [23], the authors presented an evacuation problem whose objective is to achieve evacuation of population with minimal deviations from the optimal evacuation route (shortest path). The successful realization of this objective hinges on minimizing both the frequency and magnitude of navigation errors made by evacuees. The authors further highlight that authorities may possess limited resources - both human, such as police officers or other emergency responders, and technological, such as traffic signs - that can facilitate evacuation efforts. In this context, a managed evacuation network refers to a scenario in which specific intersections within the evacuation network are regulated through the deployment of these available resources. Such a management strategy is instrumental in minimizing deviations from optimal evacuation routes, thereby ensuring that the paths taken align more closely with the shortest possible routes. Consequently, this problem can be formulated as a bi-objective optimization problem, where one objective function seeks to minimize the average length of actual evacuation routes, while the second function aims to identify the critical vertices in the evacuation network where the available resources can be effectively employed. The

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authors propose a genetic algorithm to address this issue, with the evaluation of the objective functions conducted through simulation (see Fig. 1). This simulation, which has been self-implemented, is grounded in imperative data that specifies the varying probabilities of navigation errors occurring at the nodes within the evacuation network.

Gathering navigation error data across all nodes within the evacuation network presents considerable challenges, particularly as the population requiring evacuation increases. Alternative methodologies advocate for the identification of rules or behaviors that guide evacuees in their route selection during an emergency.

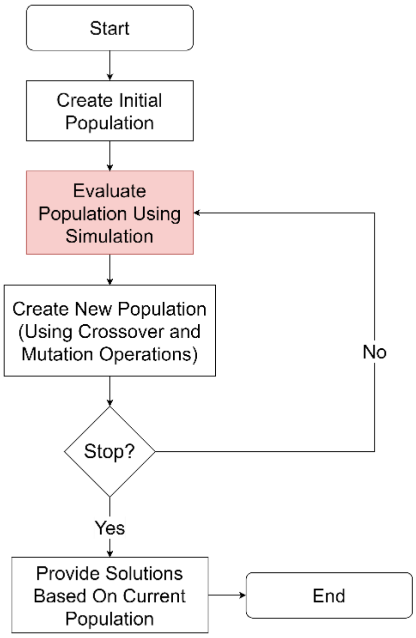

Fig. 1. A flowchart illustrating the genetic algorithm employed by Nahum, et al. [22] to address the bi-objective evacuation. The simulation phase of the algorithm is distinctly marked in red

While substantial research has been carried out in the areas of tourist behavior and evacuation management individually, the intersection of these fields has not yet been fully explored. There are four issues that warrant attention: (1) Behavioral insights in tourist evacuation: Existing research on tourist evacuation rely mainly on surveys or post-disaster analyses, often without incorporating dynamic models of real-time decision-making and navigation errors. (2) Simulation frameworks for tourists: Current evacuation models and tools (e.g., MATSim) primarily focus on local populations, with limited adaptability to the unique challenges that tourists face, such as unfamiliarity with the area and language barriers. (3) Incorporation of navigation errors: Few studies address how navigation errors - especially by tourists - influence evacuation outcomes or propose simulation-based solutions to mitigate these mistakes. (4) Policy analysis: Limited attention has been given to evaluating how pre-defined evacuation policy as opposed to undefined evacuation policy impacts evacuees' behavior, particularly for tourists.

This study aims to address these gaps by: (1) Developing a simulation framework that integrates navigation errors and tourist-specific behaviors in evacuation scenarios. (2) Introducing two novel navigation models - Random Walk and Landmark Assisted - to better reflect the decision-making challenges faced by tourists. (3) Assessing the impact of different evacuation policies (predefined vs. undefined evacuation destinations) on evacuation efficiency. And (4) Providing actionable insights into the management of intersections and the use of landmarks to optimize evacuation outcomes.

This paper uses MATSim, an extensively utilized open-source simulation tools, used in various studies related to agent-based movement, as a sophisticated replacement for the rudimentary self-implemented simulation devised by Nahum, et al. [22]. Notably, this enhanced simulation mechanism may subsequently serve as a component of the optimization process delineated by Nahum, et al. [22], facilitating a more intricate simulation of the evacuation network's dynamics. Within the context of this paper, the term 'tourist' was employed as these individuals usually encounter more difficulties in orientation than others. However, the model's applicability stretches beyond tourists to include any individuals struggling with orientation during evacuations. Conspicuously, MATSim does not have an adequate mechanism to simulate tourist behaviors, necessitating the development of specific add-ons to it. These add-on features can impersonate tourist movement patterns in distinct manners, further elaborated on within the content of this paper.

This study bridges the gap between theoretical evacuation research and practical applications, emphasizing the unique challenges faced by tourists in emergencies and providing innovative solutions to enhance safety and efficiency. The contributions of this study can be encapsulated as: (1) Development of an Innovative Simulation Framework: Modifications to MATSim are made to simulate challenges and behaviors peculiar to tourist navigation, thereby addressing a significant methodological shortfall. (2) Creation of New Navigation Models: The study focuses on designing and incorporating routers encompassing the Random Walk and Landmark Assisted components, which facilitate dynamic simulation of navigational discrepancies and landmark-oriented guidance. (3) Provision of Policy Insights: The research involves a comparative study between predefined and undefined evacuation zones, thereby establishing how policy resolutions impact the safety and efficiency of evacuation. (4) Examination of Real-World Applicability: The practical implications of handling intersection management and harnessing landmarks to enhance evacuation timelines and results are analyzed in a case study carried out in Conegliano, Italy. And (5) Construction of A Decision-Support Tool: The simulation framework devised in this study functions as an instrument for policymakers to fine-tune resource distribution and evacuation tactics, custom-made for assorted populations.

This paper is organized as follows: a literature review is presented in the next section, followed by the problem formulation and the description of the simulation tool. A case study based on a real-world network of the Italian city of Conegliano examines different behavioral evacuation scenarios and evacuation policies. The paper ends with conclusions.

1.1. Literature Review

1.1.1. Emergency Evacuation of Population

In crisis situations, the timely and efficient evacuation of affected populations is of paramount importance and entails transport to designated safe locations [24]. A variety of evacuation modalities can be leveraged, including pedestrian movement and vehicular evacuation by means of personal cars, buses, trains, aircraft, or maritime vessels. There is also potential for the integration of several modalities if necessary. The selection of the most appropriate evacuation methodology is contingent upon the geographic location of the incident, its gravity, and the physical proximity to areas of safety [25].

This research concentrates on the evacuation procedures of pedestrians, placing a particular emphasis on the diverse nature of decision-making within the population under study. Most notably, this kind of evacuation is typically seen when the geographical separation between the disaster zone and the designated evacuation zone is comparatively short.

In discussing the evacuation procedures in emergency situations involving a population shift from a specific location to one or multiple destinations, it is imperative to first examine the heterogeneity of the population to be evacuated. Humans, as a species, are characterized by a multitude of differences, yet in the context of an evacuation scenario, the pivotal factors tend to revolve around language, ethnicity, and disability.

In the context of evacuation planning, it is crucial to acknowledge three primary categories of population: local population, domestic tourists, and foreign tourists. (1) **Local population**: Among the three groups, this category is deemed as the simplest to evacuate. It is hypothesized that local population possesses knowledge of evacuation routes. Albeit the possibility of unfamiliarity, the absence of language and cultural impediments simplifies the evacuation operation. The probability of autonomous evacuation by local population in the event of a calamity is high. (2) **Domestic tourists**: This group is characterized as those visiting regions within their home country outside of their ordinary environment. Despite their unfamiliarity with evacuation routes, the lack of linguistic and cultural hindrances simplifies the evacuation process, akin to local residents. (3) **Foreign tourists**: Comparatively, this population group presents the most difficulties regarding evacuation procedures for several reasons. More often than not, these individuals are first-time visitors to the location. They are culturally diverse and frequently face language barriers, which can complicate communication with fellow evacuees and local authorities. Additionally, understanding instruction signs can pose a significant challenge. These difficulties are amplified in nations where English is not the primary language [26].

1.1.2. Evacuation Planning Using Simulation

Several factors can precipitate emergency events, including but not limited to, meteorological damage (either impacting infrastructure such as roads or occurring independently), seismic activity, acts of terrorism and warfare. These factors inevitably influence the execution of evacuation procedures. In particular, severe incidents such as earthquakes may disrupt pre-planned evacuation routes, thereby necessitating a model that accounts for potential infrastructure vulnerabilities during the formulation of evacuation policies [27].

Assessing the "efficacy" of emergency evacuation routes is a challenging process due to the complexities mentioned above. Recently, there has been a heightened focus on the utilization of transportation system simulations in emergency scenarios. This relatively cost-effective modality has the potential to reduce evacuation timelines, factoring in elements such as traffic volumes and capacity constraints [24], [28], [29].

Several elements could potentially influence the process of evacuation, including the susceptibility of infrastructure and capacity limitations, among others. These aspects can be taken into consideration before the construction of the transport network or, if such networks already are in existence, at the stage of planning the route.

Typically, the expenses incurred in the meticulous planning of infrastructure are considerably less than those associated with changes implemented post-construction (where feasible). When orchestrating a novel building structure or devising a new road network, the imperative nature of thorough planning becomes increasingly pronounced, particularly with respect to evacuation scenarios. The employment of simulation models during the planning stage emerges as an efficacious and economically efficient strategy to guarantee the comprehensive construction of infrastructure tailored to meet emergency evacuation requirements.

In the context of limited resources coupled with the objective of enhancing emergency evacuation, it becomes vital to assign priorities to infrastructure repairs, as pointed out by Hadas, et al. [30]. This precedence can be established through a methodical analysis of the infrastructure at hand, accompanied by a thorough assessment of the potential advantages and expenses of each available option.

Simulation models typically serve as a tool for examining various planning or operational options prior to making critical decisions. A cost-effective approach, these models assist in determining the potential risks and rewards of different decisions, thereby contributing to the construction of dependable models [31].

Numerous investigations have been undertaken in the realm of simulation with the aim of supplying more informed solutions to individuals responsible for decision-making. By utilizing an array of models through simulation software, stakeholders can gain a more comprehensive understanding of constraints and implement modifications to systems in an efficient and cost-effective manner, thus negating the need to invest heavily in experimental procedures.

1.1.3. Models For Planning Evacuation Networks

Hadas, et al. [30] proposed a model designed to facilitate decision-making regarding infrastructure retrofitting, particularly in the context of resource limitations. Emphasizing the crucial importance of correctly identifying and prioritizing which infrastructural elements to retrofit, they argue that this is vital for ensuring minimal evacuation times in emergencies. The model also suggests various alternative strategies using current resources. Importantly, the model prioritizes the most vulnerable and potentially influential infrastructure, taking into account their potential impact on evacuation times.

In a bid to illustrate the workings of the model, scholars applied a case study oriented on the town of Conegliano, an undersized township situated in the northern part of Italy. Within the delineated zone, they identified 51 distinct bridges, each possessing unique characteristics such as the number of lanes, type of construction, among others. These preeminent researchers inspected eight unique earthquake scenarios, each carrying disparate components of earthquake intensity and distances from the earthquake epicenter. They demonstrated the enhancement in the durability of these bridges during seismic activities after a pre-retrofit was initiated. The findings of this comprehensive elucidation underpin the indispensability of proper prioritization and guide policymakers in making informed decisions concerning infrastructure retrofitting.

The facet of evacuation time, as a component of emergency evacuation procedures, has been substantially explored in academic research. The majority of studies within this domain have typically approached the subject as an optimization issue, founded on either a minimal resource or limited flow problem [32]. Notably, Hadas and Laor [32] have indicated that government bodies, who bear the responsibility for establishing these networks, also factor in alternative objectives such as minimizing construction costs and optimizing the network's serviceability to citizens. Consequently, scholars have devised a model that tackles both the quandary of evacuation time and the challenge of minimal construction cost, acknowledging that the solution may not concurrently optimize both objectives.

According to the research conducted by Nahum, et al. [22], assessing minimal construction costs and evacuation timing is insufficient. Their study emphasizes an equally critical component: reducing navigation errors. An optimal evacuation path may exist, but the likelihood of individuals, particularly tourists, not adhering to the intended route is significant due to various issues. Frequently, authorities possess limited resources, including first responders and technological means, which can be beneficial in improving evacuation measures and curtailing navigation discrepancies. Nevertheless, how, when and where these resources can be best utilized often remain uncertain. In such instances, Nahum, et al. [22] argue for the use of simulation to strategize the allocation of these finite resources.

1.1.4. Navigation Errors During Evacuation

Evacuation refers to organized, quick and temporary removal of people from locations threatened by actual or potential emergency situations to reduce the risk of harm or death [33], [34]. An important element that directly influences the effectiveness of evacuation processes is navigation. However, navigation errors, often exacerbated during emergencies, can significantly impact evacuation time.

Various sources corroborate the fact that an increased incidence of navigation errors during evacuation correlates with a substantial extension in overall evacuation time [22], [35]–[37]. Among the myriad factors that contribute to navigation error, unfamiliarity with the physical layout of the area and ambiguous evacuation signage or instructions often prevail. Disorientation, panic, confusion, and misinformation similarly play a role in such errors and subsequent delays in evacuation time [38].

Various research papers scrutinize the broad concept of navigation errors and their severe implications on evacuation times. Whilst some studies focus more on humans' built environment and its design, others focus on human behavior under stress, age-related cognitive decline, individual differences in navigation strategy and spatial ability. The overarching themes of the papers are to contemplate actions to rectify or crank down such navigation errors to ensure safer and more efficient evacuation times [37], [39], [40].

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In a stressful and time-sensitive situation such as an emergency evacuation, these errors can result in a wide array of negative outcomes. Apart from the obvious increase in evacuation time, the increased congestion caused by navigation errors can also lead to physical injuries or fatalities due to stampedes and falls [41]. Consequently, the survivability rate decreases in line with increased evacuation times.

Moreover, in situations where emergency responders attempt to access the site for rescue and relief operations, navigation errors that result in longer evacuation times can hamper these efforts, thereby potentially increasing the overall impact of the disaster [42]. This is especially prevalent in building evacuations, where the delayed exit of occupants can directly interfere with the intervention of fire-fighting teams, thus escalating the level of risk.

Given such profound implications of navigation errors during evacuations, it is essential to develop a solid understanding of navigation during emergencies and incorporate this knowledge into strategic planning and preventive measures. This will include policies and procedures that ensure clear, standardized evacuation instructions, well-rehearsed evacuation drills, and proper spatial design. This proactive measure may contribute to a considerable reduction in navigation errors, thus leading to faster evacuation times and higher survival rates during emergency situations.

2. Method

2.1. Problem Formulation

The shortest path problem (SPP) is an essential issue in network theory, which involves identifying a path between two or more nodes where the sum of the weights of its comprising arcs is kept to a minimum. Frequently, in real-world scenarios, one must take into account various types of uncertainties, such as system failures, maintenance issues, and other variables. Probability theory has proven useful in addressing these elements of randomness. As of now, the majority of studies that involve randomness primarily focus on randomness on the arc, in what is known as stochastic SPP (SSPP). Typically, this relates to variations in travel time or cost, which may be affected by traffic, weather conditions, and payload, among other factors [43], [44].

An alternative interpretation of the stochastic shortest path problem is the probabilistic shortest path problem (PSPP). This version is concerned with determining an a priori shortest path between a source node s and a sink node t in a complete network. In any given instance of the problem, only a subset of intermediate nodes - selected based on a specific probability law - may be used to travel from s to t [45]. Further study by Jaillet [45] demonstrated the complexity of the problem, proving it to be NP-hard.

Various strategies have been proposed to address the inherent unpredictability of the probabilistic shortest path problem in practical scenarios. The most basic tactic, “random walk”, stipulates that, for any given node, there is an equal likelihood of selecting any of the connecting arcs [46], [47]. Yet, this assumption may not always hold true. The probability of choosing certain arcs over others can vary, subject to the network's framework. For instance, arcs boasting a larger capacity may receive preferential treatment. Observations about human behavior indicate further nuances. Often, when determining their routes, individuals demonstrate an inclination towards movement in straight lines. This suggests an alternative approach where, at each node, the arc that continues the trajectory of the inbound arc is prioritized. This heuristic hypothesis, further highlighted by Sabashi, et al. [48], opens up new perspectives on the probabilistic shortest path problem.

Addressing the issue of prolonged evacuation durations, particularly for tourists unfamiliar with the area, entails the implementation of enhanced navigational aids at strategic junctures. Such aids might include physical signage, improved intersection design, or the strategic positioning of first responders. The allocation of resources to facilitate these solutions should be optimized given the bi-objective problem of reducing evacuation time while minimizing resource deployment. The criticality of optimal resource allocation is underpinned by the limited availability of first responders [22]. Another avenue to consider includes the use of landmarks as navigational aids during evacuation [49]–

[51]. In such circumstances, potential escape targets such as tall buildings, antennas, or other visible constructs can be identified from a distance. Consequently, at each decision point, routes can be prioritized based on their alignment towards the evacuation endpoint.

The forthcoming section will provide a mathematical formulation of the problem at hand as described in this paper. In order to enhance readability and comprehensibility, a compilation of all the notations utilized is presented. An explanation for the necessity and usage of each notation is given later in this chapter.

Table 1. List of notations used in the mathematical formulation

$G(V,E)$	A connected graph
$V = 1,2,..n$	Set of nodes
$E = \{e_{ij}: i \neq j, i,j \in V\}$	Set of edges
O	Origin node
D	Destination node
e_{ij}	An edge from node i to node j
e_{ij}^{c}	Cost of moving from node i to node j
e_{ij}^{p}	Probability of choosing the edge that links nodes i and j.
P_{OD}	Path from node O to Node D.
P_{OD}^{c}	Cost of the path P_{OD}.
S_{OD}	Deterministic shortest path from O to D.
W	Set of paths from O to D.
W^{C}	Cost of a path in the set W.
$\overline{W}^{C}$	Average cost of all paths in the set W.
x_i	Decision variable, equals to 1 if node i is managed and 0 otherwise.

2.1.1. Navigation Error Formulation

Assuming a comprehensive understanding and analysis of tourist behavior, it becomes feasible to formulate evacuation policies accordingly. Considering the evacuation trajectory from the initial point to the final destination is designed to be the shortest route, any erroneous diversion while following this course could potentially increase the total travel distance.

The problem under study can be represented through a connected graph depicted as $G(V,E)$. In this graph model, $V = 1,2,..n$ comprises a collection of nodes, while $E = \{e_{ij}: i \neq j, i,j \in V\}$, constitutes a collection of edges. Every edge, illustrated as e_{ij}, is affiliated with two values. The first value, e_{ij}^{c}, symbolizes the cost (which could be time, distance, etc.) involved in the passage from node i to node j. The second value, e_{ij}^{p}, denotes the likelihood of choosing the edge that links nodes i and j. To clarify, every node within V, represented as $i \in V$, the probabilities of the edges linked to it (represented as $e_{ij} \in E: i \neq j, i \in V$) are required to adhere to the condition $\sum_{e_{ij} \in E} e_{ij}^{p} = 1$. These probabilities offer an empirical representation of the tourists' navigation errors. Fig. 2 (left) illustrates the decision-making at an intersection (current location), in which the evacuee can select to take left, with a probability of 0.4, take right (probability 0.5), or turn around (probability 0,1).

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The notation $P_{OD} = e_{O,k}, e_{k+1,k+2}, \dots, e_{k+m,D}$ designates a path from an origin node, denoted as $O \in V$, to a destination node, denoted as $D \in V$, within a given vertex, V. This path includes a subset of intermediate nodes represented by the variable k, where k is less than n (n being the total number of nodes in the graph). In terms of path analysis, the cost of the path P_{OD} is expressed as P_{OD}^{c}, and is equal to $\sum_{e_{ij} \in P_{OD}} e_{ij}^{c}$.

The deterministic shortest path from O to D, S_{OD}, is a path P_{OD} which minimizes P_{OD}^{c}. However, the stochastic shortest path is realized by random walks deviating from S_{OD}, and can be defined using chance constraints as follows. Let W be a set of paths, from O to D. Let W^{C} denotes the cost of a path in the set W such that $P\left(P_{ij}^{c}: P_{ij} \in W \leq W^{C}\right) \geq \alpha$, with $W^{C} \geq S_{OD}$.

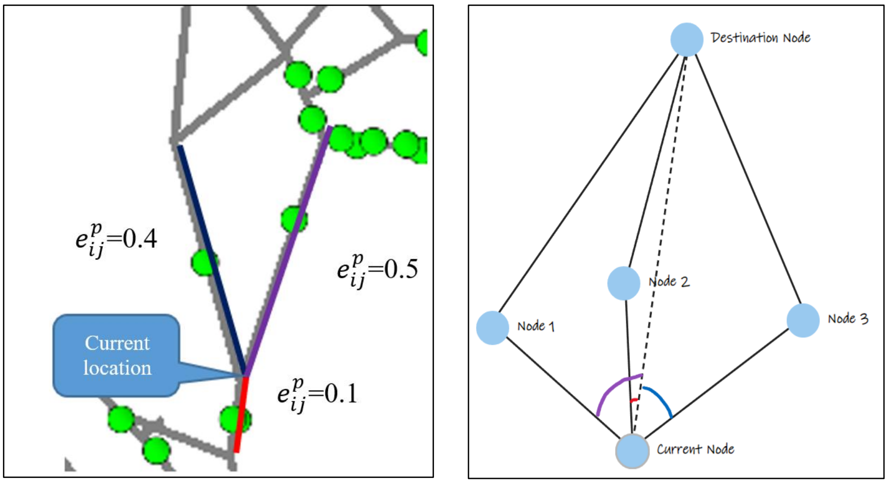

Fig. 2. Navigation Error at an Intersection (left) and Landmark Assistant Evacuation (right)

2.1.2. Managed Evacuation

A managed evacuation is a situation where specific intersections (nodes) are regulated (managed) with the aid of first responders or via the utilization of road signs. This management strategy aids in minimizing deviations and as a result, it facilitates routes that adhere more closely to the shortest possible path.

The imperative concern is to ascertain which nodes $i \in V$ will be managed towards the destination node, D (these can be perceived as the managed intersections). For each managed intersection, i, the probabilities associated with its corresponding edges are revised. Specifically, if an edge e_{ij} is on the shortest path from node i to node D ($e_{ij} \in S_{iD}$), its corresponding probability $e_{ij}^{\bar{p}}$ is set to unity (i.e. $e_{ij}^{\bar{p}} = 1$). Conversely, for any edge connected to node i which is not on the shortest path from node i to node D, $e_{ik} \notin S_{iD}$, its probability, notated as $e_{ik}^{\bar{p}}$, is nullified to zero (i.e. $e_{ik}^{\bar{p}} = 0$)

2.1.3. Landmark Assisted Evacuation

As described above, each edge e_{ij} is associated with two values: (1) e_{ij}^{c} – the cost of traveling from node i to node j, and (2) e_{ij}^{p} – the probability of selecting the edge from node i to node j.

The value e_{ij}^{p} can be obtained in various ways. It can be empirically obtained using observations, or it can be determined using various heuristics. One such heuristic, used in this research, is the landmark-assisted evacuation [49], [51], which can be applied in cases where the destination node is visible from a distance.

In this heuristic, e_{ij}^{p} is determined by the angle between the edge e_{ij} and the imaginary edge formed by connecting the current node to the destination node, as illustrated in Fig. 2. In this heuristics, smaller angles are preferred. Following Fig. 2 (right), the evacuee at the current node, will have a higher probability of selecting the arc leading to node 2.

2.1.4. Objective functions

Two objectives are given priority in this study. The primary goal, as formulated in Eq. (1), aims at reducing the number of managed nodes. In this equation, the decision variable is denoted as x_i, which is equals to 1 if node i is a managed node, the value is 1, otherwise it is equal to 0 ($x_i \in \{0,1\}\ \forall i \in \{1, \dots, n\}$).

$$\text{Min } Z_1 = \sum_{i=1}^{n} x_i \tag{1}$$

The second objective, expressed in Eq. (2), is about minimizing the divergence between the paths determined through random walks (W^C) and the shortest route (S_{OD}). As W^C signifies the cost of any path from node O to node D, a more appropriate way to express this objective function could be to lessen the gap between the highest cost of a random walk (max (W^C)) and the shortest route. Alternatively, as used in this paper, it could be finding the difference between the average cost of all random walks ($\overline{W}^C$) and the shortest route.

$$\text{Min } Z_2 = \overline{W}^C - S_{OD} \tag{2}$$

As the aim of this paper is to introduce a simulation framework, optimal managed evacuation is not considered. However, the effect of managing several intersections is investigated.

2.2. Simulation Framework

As part of the study, a simulation model was constructed. The simulation model describes the movement of all the entities (evacuees) in the network, considering the chance of those entities making navigation mistakes. In this research, MATSim was used as the simulation tool.

MATSim, or Multi-Agent Transport Simulation, is an open-source simulation framework employed for modeling transportation systems [52], [53]. It utilizes a multi-agent approach to replicate the daily activities of individuals, allowing for nuanced insights into transportation dynamics. The framework offers a modular environment where various add-ons can be integrated to enhance its functionality by extending the core simulation capabilities, facilitating the integration of external data sources, or incorporating advanced modeling techniques. Research utilizing MATSim spans various domains, including urban planning, traffic management, and sustainability analysis. One critical area of research involves evaluating the impact of various transport policies on travel behavior and congestion. Researchers have employed MATSim to simulate scenarios involving public transport enhancements, congestion pricing, and infrastructure development, thereby providing empirical evidence to guide policy decisions. Additionally, MATSim has been utilized in studies assessing the resilience of transportation networks in the face of disruptions, allowing planners to better understand and mitigate the effects of events such as natural disasters or pandemics [54]–[58].

2.2.1. Optimal Walk

To accurately assess the outcomes of the navigation models, it is necessary to know the optimal evacuation routes. In this study, MATSim was used to find the optimal evacuation routes in cases where there is a set of origin-destination nodes.

MATSim uses Dijkstra's algorithm [59], a commonly used algorithm in network analysis, for finding the shortest paths between the origin and destination nodes in a transport network. This algorithm compares all possible paths in the network and then selects the path with the least travel time or distance.

The central aspect of MATSim is that it simulates the actions and interactions of multiple agents as they navigate the transportation network. This involves generating a series of routes for each individual agent based on the chosen network attributes (distance, travel time, traffic volume, etc.). Once the initial routes are generated, a series of iterations are run, modifying these routes based on the overall traffic conditions and individual agent behavior.

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During each iteration, the model uses Dijkstra's algorithm to re-route the agents, continually seeking the path that will minimize the specific cost function. Over time, as the model iterates, the system will ideally reach an equilibrium, where no agent can improve its situation by changing its behavior, given other agents' actions.

2.2.2. RandomWalk

One of MATSim's major components is the network router. A MATSim router is essentially a routing algorithm that suggests the quickest, least congested or shortest path for an individual "agent" or user in a traffic network based on certain predefined parameters such as travel time, distance, or other factors.

In MATSim, the decision of the router determines the routes and timings of the agents within the network - taking into account elements such as vehicle type, departure time, and network conditions - in order to simulate realistic traffic flows. The tool allows for iterative simulations where the behavior might change based on the experiences of previous intervals.

Built-in routers use mathematical algorithms and data analytics, making use of the Dijkstra algorithm or its variations (like the A* algorithm) to suggest the best route for an agent. In essence, the router is an essential part of creating simulations of travel behavior which can benefit policymakers, transport engineers, and others who require an understanding of complex transport networks.

Unfortunately, MATSim lacks the capability of random walk. One of the advantages of MATSim as an open-source project is its ability to add user implementations of various add-ons. In this case, an add-on, which implements a new random walk was developed.

The random walk add-on router selects the outgoing arc on the fly based on a probability vector as defined in the navigation error formulation section. Specifically for this work, the router selects the next edge in the path randomly. MATSim keeps selecting edges randomly until it reaches the destination node. This router can be further extended and consider the individual behavior of the evacuee (tourist or not) as proposed in [48].

2.2.3. Landmark Assisted Evacuation

In many cases dealing with evacuation, the evacuation zones will be such that they can be identified from a distance [49]–[51]. Whether by a tall building, a tall antenna, or some other object that can be seen from a distance. In some cases, it is even possible to inflate a balloon that can be seen from a distance, and which will serve as a marker to which the evacuees directed themselves [60].

MATSim lacks the capacity of navigation by landmarks. Therefore, once again, an add-on, which implements this approach was developed. This new add-on implements a new router, which for every entity at every node checks the angles between the various links at the current location and the destination node (evacuation zone). Then, the router selects, with a higher probability, the next link such that the angle between the link and destination node is the smallest (see Fig. 2 (right)).

3. Results and Discussion

3.1. Case Study

To assess the framework, a real-world case study was conducted. The analysis is focused on an urban area, the municipality of Conegliano, a town of 40,000 inhabitants located in the northern part of the province of Treviso, north-eastern Italy [30]. This location was chosen due to its significant seismic hazard. The selected test area encompasses a diverse collection of 51 bridges, which represent a variety of typologies, including single-span and multi-span designs, constructed from materials such as concrete, steel, and masonry. These bridges also display various design configurations, both straight and skewed. Furthermore, this area has been utilized in several evacuation and other case studies (e.g., [30], [61]–[64]), thus allowing for the integration of insights from prior research. The results of this study can subsequently be compared to results from earlier research papers, contributing to a more comprehensive understanding of the subject. Fig. 3 presents the road network components, including the location of the origins and destinations (shelters).

3.1.1 Scenarios

Three different models were used: (1) optimal evacuation, (2) random walk evacuation, and (3) landmark-assisted evacuation. For each scenario, two evacuation policies were examined (1) a predefined evacuation zone and (2) an undefined evacuation zone. The former policy assigns each evacuee to a predefined zone. This can be related to limited capacity at the evacuation zones, instructions provided to tourists at the hotels, etc. The latter policy is relevant when only general instructions are provided or when capacities are not a major concern.

Three parameters were examined for each of the evacuation models within both evacuation policies: (1) Average evacuation time, (2) Total evacuation time, and (3) Number of evacuees evacuated within the first 90 minutes.

Finally, managed evacuation has been examined as well. For each scenario, after an analysis of the results of the previous simulations, several nodes were manually selected to be managed. A second simulation was conducted to determine the effect of managed evaluation on the evaluation time.

3.1.1.1. Optimal Evacuation

First, MATSim was used to find the optimal evacuation routes. This is done using MATSim's internal capabilities of finding the shortest paths. Using 2000 entities (evacuees), equally divided between the two origins nodes, for the predefined evacuation policy, the average evacuation time found was 50 minutes and 14 seconds with a standard deviation of 26.7 minutes. Following a duration of one and a half hours, there remained a total of 124 entities to be evacuated. The total time required to evacuate all entities amounted to one hour and forty-five minutes. The optimal evacuation routes are illustrated in Fig. 3.

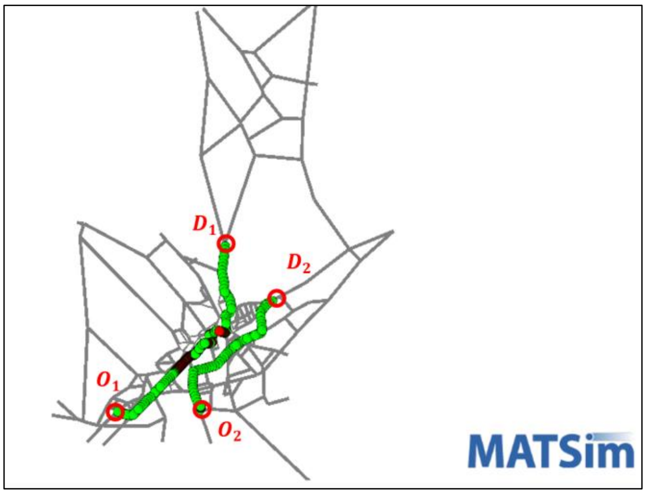

Fig. 3. The optimal evacuation routes for predefined evacuation destinations, for the Conegliano road network (Hadas et al., 2015) with origin nodes O_1 and O_2 and destination nodes D_1 and D_2

3.1.1.2. Random Walk

Next, MATSim was configured to use the new random walk router. First, the predefined evacuation destination policy where used. In this case, every entity has a defined evacuation destination and cannot be evacuated to other evacuation zones (even by mistake). The average evacuation time in this case was 544 minutes and 36 seconds, with a standard deviation of 434 minutes. Following a duration of one and a half hours, there remained a total of 1915 entities to be evacuated. The total time required to evacuate all entities amounted to 58 hours and twenty minutes.

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3.1.1.3. Landmark Assisted Evacuation

Finally, MATSim was run using the “Landmark assisted” router, which means that at every intersection each entity chooses the road with the closest angle to the destination. Once again, first, only the predefined evacuation destination policy was used. The average evacuation time in this case was 82 minutes and 34 seconds, with a standard deviation of 44.7 minutes. Following a duration of one and a half hours, there remained a total of 612 entities to be evacuated. The total time required to evacuate all entities amounted to three hours and thirty minutes. It is clear from the results obtained for the two routers that the total evacuation time in the case of a landmark-assisted evacuation is significantly lower compared to a random walk.

3.1.1.4. Hybrid Evacuation Policy

In the actual world, the ability to utilize landmarks for navigation purposes is not feasible at all stages of navigation, either because of visibility problems, navigation mistakes, or other reasons. To simulate such scenarios, a hybrid method, which combines both “Random Walk” and “Landmark Assisted” evacuation, was examined as well.

For the purpose of analysis, a series of five separate simulations were conducted. In the first simulation, the route selection at 90% of the nodes was determined based on landmarks, while for the remaining 10%, the route selection was predicated on random walk conditions. After that, in the second simulation, the ratio changed; the route selection at 70% of the nodes was contingent upon landmarks, while at the remaining 30% of nodes, the route selection was reliant on a random walk algorithm. In the third simulation, an even split was observed. Route choice was implemented based on landmarks for 50% of nodes, and random walk principles were utilized for the remaining 50%. The fourth simulation saw a continuation of this trend, with the proportion of route selection dependent on landmarks decreasing to 30%, with random walk processes employed at the remaining 70% of nodes. Finally, in the last simulation, landmark-based route choice was at its lowest at 10%, while reliance on the random walk increased, comprising 90% of the route selection process at nodes. The outcomes of these simulations provide insights into the dynamic interplay between these two navigation strategies and their relative impacts on route selection outcomes.

Table 2. Results for the various hybrid scenarios

Percentage of nodes using landmark navigation	Percentage of nodes using random walk	Average evacuation time (hours)	Number of entities still en route after 1.5 hours	Time needed to evacuate all entities (hours)
90	10	01:01:11	325	02:40:00
70	30	00:55:31	127	02:30:00
50	50	01:05:56	300	03:50:00
30	70	01:35:42	847	05:35:00
10	90	03:58:00	1677	31:06:14

The results of the various hybrid scenarios are summarized in Table 2 and Fig. 4 (top). The findings reveal a significant improvement in outcomes when a 70:30 ratio of the "Landmark Assisted" router to the "Random Walk" router is applied, as compared to a 100% application of the former. This is likely due to congestion resulting from universal reliance on similar routes. Conversely, when only 30% of the time the "Landmark Assisted" router is selected (and the "Random Walk" router is selected 70% of the time), performance deteriorates greatly. However, it must be noted that these results are contingent upon the specific attributes of this particular network and may vary under different circumstances.

Fig. 4 (bottom) offers a comparative view of the entities progressing toward the evacuation zone within the initial three hours of the evacuation phase. This is represented as a time function in all cases of hybrid use where the percentage data symbolizes the chance of the "Landmark Assisted" router being selected at each node. Notably, in the case study where entities opt for the "Landmark Assisted" router 50% of the time (and the "Random Walker" router at analogous intervals), after the first 1.5 hours of evacuation, there are still 387 evacuees en route to the evacuation zones. This contrasts starkly with the 606 entities successfully evacuated within the same timeframe but under a 100% application of the "Landmark Assisted" router.

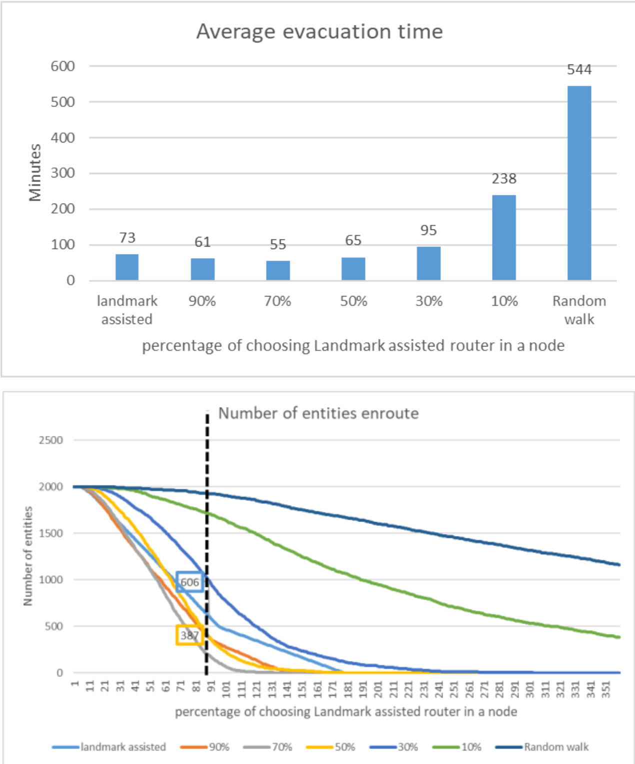

Fig. 1. The average evacuation time as a function of the routers used (top) and the number of evacuees enroute to the destination point as a function of time and the router used (bottom)

3.1.2. Validity of the Results

To examine the validity of the results, a validity test was carried out using some of the scenarios described in the previous sections. Each scenario was subjected to 100 simulations. The results of these simulations were utilized to calculate the average evacuation time and standard deviation for each of the scenarios.

Table 3. Results for the validity tests

Percentage of nodes using Landmark navigation	Percentage of nodes using random walk	Average evacuation time (hours)	Standard Deviation (in hours)	Standard Deviation (in percentage)
90	10	01:01:45	0.62	0.0101
70	30	00:55:02	0.54	0.0099
0	100	09:16:22	14.25	0.0256

From Table 3, which summarizes the results of the validity tests, it can be discerned that the standard deviation is notably minute, amounting to less than three percent in instances where all participants use random walk navigation, and approximating one percent in other scenarios. This observation substantiates that the results are adequate for comprehending the general trends, therefore obviating the necessity for additional runs.

3.1.3. Evacuation Policy Analysis

Policymakers can choose between two evacuation policies, either each evacuee should be evacuated to a specific evacuation zone (predefined policy), or each evacuee can be evacuated to any evacuation zone it chooses to (undefined policy).

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A comparative analysis was conducted between the two policies by utilizing an assortment of scenarios. In the first scenario, all evacuees use a random walk to determine their evacuation routes. In the second scenario, all evacuees use a landmark-assisted evacuation to determine their evacuation routes. The next three scenarios include a combination of the two tools for determining evacuation routes. In the third scenario, 70% of the nodes use landmark-assisted evacuation for route planning, whereas the rest apply the random walk method. Similarly, in the fourth scenario, 50% of the nodes employ the landmark-assisted evacuation tactic and the rest make use of the random walk approach. Finally, in the fifth scenario, 30% of the nodes apply the landmark-assisted evacuation strategy, while the remaining use the random walk technique.

Fig. 5 shows the average evacuation time for the five scenarios, for both the undefined and predefined policies, as a function of time with the percentages representing the probability of choosing the "Landmark Assisted" router at each node. It can be seen that the undefined policy is preferred as the probability of using the "Random Walk" router increases. It means that with the undefined policy, the evacuee has a higher chance of reaching a safe zone "accidently", i.e., two potential destinations versus one.

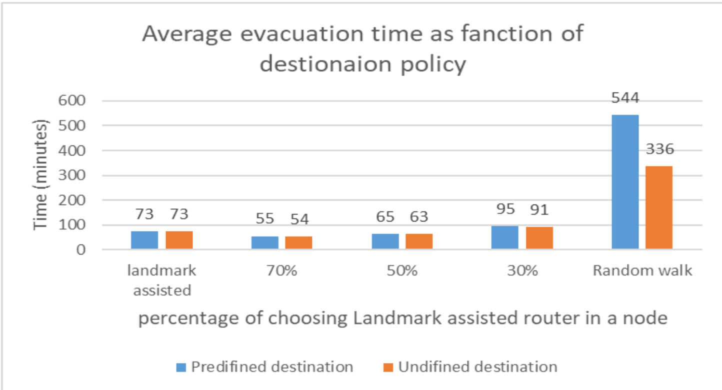


Fig. 5. The average evacuation time as a function of the router used and the evacuation policy

3.1.4. Managed Evacuation Analysis

The analysis of the results shows that there are several intersections in which a selection of a specific road (when using the landmark-assisted router) results in an increase in evacuation time. If these nodes are managed the evacuation time can be reduced. Fig. 6 (left) illustrates that issue. It can be seen that the evacuees from O_1 to D_1 divert to the blue circle area due to the orientation to D_1 when it can be identified from afar (landmark assisted), resulting in a longer evacuation route.

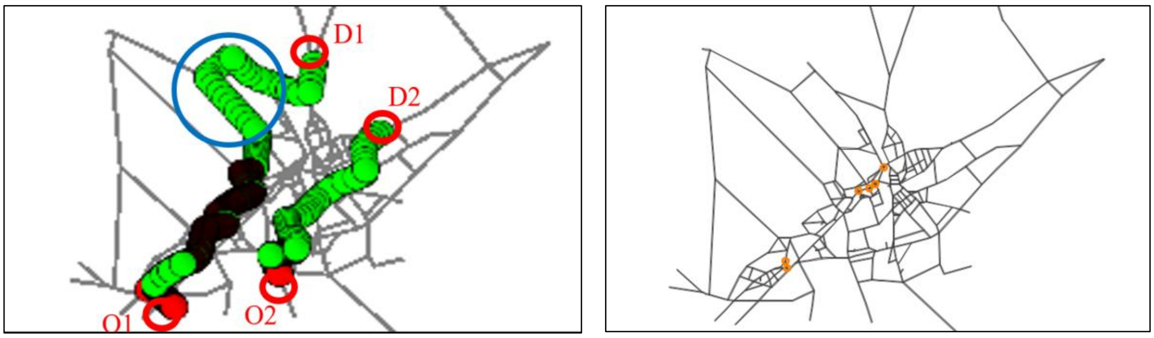


Fig. 6. The dispersal of the evacuees in a landmark-assisted method (left) and The six managed intersections, marked orange (right)

Fig. 6 (right) presents the intersections that were manually selected to be managed, while Fig. 7 presents a comparison of the number of evacuees en route to the evacuation zone as a function of time in the case of managed evacuation. It can be seen that managing intersections combined with the "Landmark Assisted" router, results in lower evacuation time.

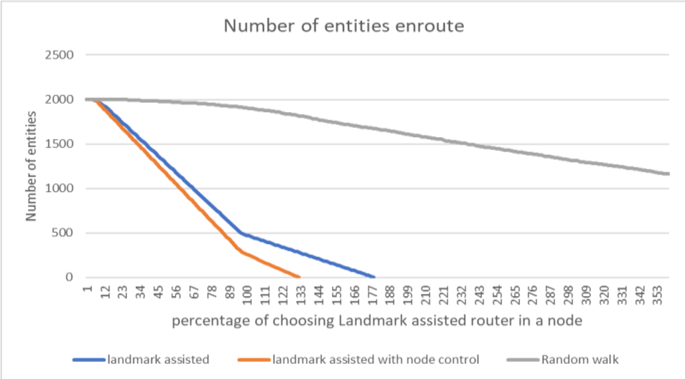


Fig. 7. The number of evacuees en route to the evacuation zones as a function of the router used and the intersection management policy

3.2. Discussion

Table 4 provides a summary of the results obtained for each router (optimal, random walk, and landmark assisted) and evacuation policy (predefined evacuation zone and undefined evacuation zone).

Table 4. Average evacuation time as a factor of the tourist behavior and destination eye contact

Router Model	Evacuation Policy	Average Evacuation Time (min.)	Standard deviation
Optimal	Predefined	50	26.7
	Undefined	50	26.7
Random Walk	Predefined	544	434.0
	Undefined	336	254.1
Landmark assisted	Predefined	73	44.7
	Undefined	73	44.7
	Managed Evacuation	60	32.9

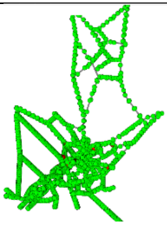
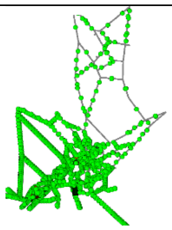
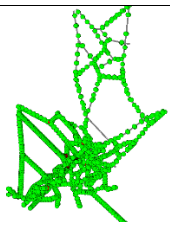
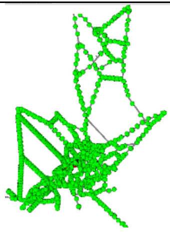
The results reveal that an unoriented tourist following a random walk route under a "predefined evacuation zone" policy will take 10 times longer to evacuate, taking up to 544 minutes as opposed to 50 minutes if they were to follow the optimal evacuation route. Moreover, by implementing an easy-to-apply landmark-assisted evacuation, the time spent evacuating can significantly be reduced to 73 minutes from 544 minutes — roughly 7.5 times faster.

The "undefined evacuation zone" policy can reduce the evacuation time of an unoriented tourist (following a random path) from 544 minutes to 336 minutes. This is a 60% improvement and less than 7 times the most efficient evacuation time. However, when landmark-assisted evacuation is used, the "undefined evacuation zone" policy has no impact on the evacuation time, which remains at 73 minutes.

Additionally, the evacuation time can be reduced by managing certain intersections of the evacuation network, as shown by the utilization of the "Landmark Assisted" router. The “Landmark Assisted” router assumes that when following the evacuation route, at each intersection, the road with the closest angle to the destination (the landmark) should be chosen. However, in some cases, this assumption can lead to longer evacuation routes, because of large detours as demonstrated in Fig. 6. Managing intersections where wrong choices can occur will prevent those wrong choices, resulting in a shorter evacuation route – 60 minutes compared to 73 minutes.

The distribution of evacuees for the "Random Walk" and "Landmark Assisted" routers, as well as the two evacuation policies, are presented in Table 5. It can easily be observed that evacuees are less dispersed and the evacuation time is shorter when using the "Landmark Assisted" router as opposed to the "Random Walk" router.

Table 5. Location of evacuees as a function of time for each scenario and policy

Evacuation time (hours) / Router and policy	**1**	**2**	**6**
Random & predefined			
Random & undefined			
Landmark assisted & predefined			
Landmark assisted & undefined			
Landmark assisted & predefined & managed			

The findings can be condensed as such: the selection method of the evacuation route by the evacuees influences the duration of the evacuation. Making an informed decision about the evacuation route (using landmarks as a guide, for example) can decrease evacuation times, though it can also restrict the choice of evacuation zones. For decision-makers, the choice of evacuation zones is significant. An evacuation zone that is easily identifiable from afar, or an optimal (or near optimal) evacuation route can be easily found for it, based on clear signage, is crucial for minimizing evacuation times. Recognizing intersections in the evacuation network where mistakes in navigation may occur, potentially prolonging evacuation times, is vital. Decision makers should consider marking these locations or guiding evacuees through them to avoid these errors and lessen evacuation times.

This study only employed two strategies for selecting evacuation routes, so evacuation routes could potentially vary based on different strategies or a combination of strategies in practical scenarios. Assessing various evacuation networks might also yield diverse results. These constraints underline the importance of analyzing evacuation populations and evacuation networks and developing informed evacuation routes to facilitate swift and efficient evacuation of different populations during emergencies.

While the study presents a novel simulation framework for emergency evacuations and introduces innovative routing models, several limitations must be acknowledged to contextualize its findings and guide future research efforts: (1) Generality of Simulation Results: The results of this study are based on a single case study conducted in Conegliano, Italy. Although the network and conditions represent a realistic scenario, the generalizability of the findings to other urban environments, disaster types, or populations may be limited. Different regions may exhibit unique infrastructural and cultural characteristics, impacting evacuation dynamics. Studies have shown that factors like road network density, population density, and cultural familiarity with evacuation protocols significantly influence evacuation efficiency [25]. Future research could extend this framework to various urban and rural settings to validate its broader applicability. (2) Simplistic Navigation Models: The simulation employs two primary navigation models - Random Walk and Landmark Assisted - to reflect evacuee behavior. While these models provide valuable insights into navigation errors, they represent extreme cases of evacuee behavior. Real-world evacuations often involve a mixture of behaviors, influenced by individual decision-making, social interactions, and external guidance [16], [26]. More complex behavioral models incorporating factors such as group dynamics, panic responses, and information-sharing among evacuees could enhance the accuracy of the simulations. (3) Resource Constraints and Intersection Management: The study highlights the importance of managing key intersections to improve evacuation outcomes. However, the analysis assumes manual selection of intersections for management, which may not be practical in large-scale evacuations. Research has demonstrated that algorithmic approaches, such as optimization models for resource allocation, can effectively identify critical intersections [22], [32]. Integrating such algorithms into future studies could improve decision-making under resource constraints. (4) Uncertainty in Navigation Error Data: The navigation error probabilities used in the simulations are derived heuristically or based on limited empirical data. These assumptions may not fully capture the variability in human behavior during emergencies, especially under high-stress conditions. Literature emphasizes the need for more empirical data on navigation errors, particularly in diverse populations such as tourists, elderly individuals, and persons with disabilities [38], [49]. Developing a robust dataset through field experiments or real-world evacuation drills would enhance the reliability of the simulation outcomes. (5) Evacuation Policy Considerations: The study compares predefined and undefined evacuation policies but does not explore hybrid or dynamic policy implementations, where evacuees are directed to different zones based on real-time conditions. Dynamic evacuation management, supported by technologies like GPS and real-time tracking, has shown promise in optimizing evacuation routes and reducing congestion [34], [37]. Incorporating dynamic policy models into the framework could improve adaptability to evolving disaster scenarios. And, (6) Dependence on Landmarks: While the Landmark Assisted model demonstrates significant improvements in evacuation efficiency, its effectiveness relies heavily on the availability and visibility of landmarks. Natural disasters, such as earthquakes or storms, may obscure landmarks, rendering this method less effective. Wunderlich and Gramann [51] highlight the need for redundancy in navigation aids, including digital tools like augmented reality or GPS-based systems, to complement physical landmarks.

To address these limitations, future research could extend the framework to diverse geographic and infrastructural contexts, incorporate advanced behavioral models and multi-modal evacuation strategies, utilize optimization algorithms for resource allocation and intersection management, collect comprehensive navigation error data across varied populations and disaster scenarios, and explore the integration of dynamic, real-time evacuation policies supported by digital technologies.

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By addressing these gaps, future studies can enhance the robustness and practical applicability of simulation frameworks for emergency evacuations. This iterative process of refinement aligns with the broader literature, which emphasizes the need for adaptable, data-driven approaches to disaster management [36], [57].

4. Conclusion

This paper presents a novel simulation framework for emergency evacuations, addressing the unique challenges faced by tourists during crises, such as navigation errors and decision-making under stress. By utilizing MATSim, supplemented with two newly developed navigation models - Random Walk and Landmark Assisted - the paper demonstrates significant improvements in evacuation efficiency through the use of landmark-assisted routing. The results reveal that while optimal evacuation routes minimize time, landmark-assisted navigation drastically reduces evacuation durations compared to random walk methods, even under predefined and undefined evacuation policies. Furthermore, managing key intersections further enhances evacuation efficiency by minimizing navigation errors. This research emphasizes the importance of integrating behavioral insights, resource allocation, and dynamic evacuation strategies into emergency planning to optimize safety and evacuation outcomes for diverse populations, including tourists.

Acknowledgments

This research was supported by a grant from the Ministry of Science & Technology, Israel & the Japan Science and Technology Agency (herein referred to as "JST"). This work originates from the Master's thesis of Omri Mayost, under the able direction of Dr. Yuval Hadas. Dr. Hadas tragically passed away in February 2024, barely days after his 57th birthday celebration. The authors dedicate this paper to the cherished memory of Dr. Hadas.

References

[1] J. Villegas, C. Matyas, S. Srinivasan, I. Cahyanto, B. Thapa, and L. Pennington-Gray, "Cognitive and affective responses of Florida tourists after exposure to hurricane warning messages," *Nat. Hazards*, vol. 66, no. 1, pp. 97–116, Mar. 2013, doi: 10.1007/s11069-012-0119-3.

[2] I. Cahyanto and L. Pennington-Gray, "Communicating Hurricane Evacuation to Tourists," *J. Travel Res.*, vol. 54, no. 3, pp. 329–343, May 2015, doi: 10.1177/0047287513517418.

[3] T. E. Drabek, "Disaster evacuation responses by tourists and other types of transients," *Int. J. Public Adm.*, vol. 22, no. 5, pp. 655–677, Jan. 1999, doi: 10.1080/01900699908525400.

[4] L. Goeldner-Gianella, D. Grancher, Ø. Robertsen, B. Anselme, D. Brunstein, and F. Lavigne, "Perception of the risk of tsunami in a context of high-level risk assessment and management: the case of the fjord Lyngen in Norway," *Geoenvironmental Disasters*, vol. 4, no. 1, p. 7, Dec. 2017, doi: 10.1186/s40677-017-0068-y.

[5] C. Matyas, S. Srinivasan, I. Cahyanto, B. Thapa, L. Pennington-Gray, and J. Villegas, "Risk perception and evacuation decisions of Florida tourists under hurricane threats: a stated preference analysis," *Nat. Hazards*, vol. 59, no. 2, pp. 871–890, Nov. 2011, doi: 10.1007/s11069-011-9801-0.

[6] B. Balcik and B. M. Beamon, "Facility location in humanitarian relief," *Int. J. Logist. Res. Appl.*, vol. 11, no. 2, pp. 101–121, Apr. 2008, doi: 10.1080/13675560701561789.

[7] A. C. Y. Li, L. Nozick, N. Xu, and R. Davidson, "Shelter location and transportation planning under hurricane conditions," *Transp. Res. Part E Logist. Transp. Rev.*, vol. 48, no. 4, pp. 715–729, Jul. 2012, doi: 10.1016/j.tre.2011.12.004.

[8] P. Murali, F. Ordóñez, and M. M. Dessouky, "Facility location under demand uncertainty: Response to a large-scale bio-terror attack," *Socioecon. Plann. Sci.*, vol. 46, no. 1, pp. 78–87, Mar. 2012, doi: 10.1016/j.seps.2011.09.001.

[9] H. D. Sherali, T. B. Carter, and A. G. Hobeika, "A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions," *Transp. Res. Part B Methodol.*, vol. 25, no. 6, pp. 439–452, Dec. 1991, doi: 10.1016/0191-2615(91)90037-J.

[10] A. Stepanov and J. M. Smith, "Multi-objective evacuation routing in transportation networks," *Eur. J. Oper. Res.*, vol. 198, no. 2, pp. 435–446, Oct. 2009, doi: 10.1016/j.ejor.2008.08.025.

[11] J. Barcelö, L. Montero, L. Marqués, and C. Carmona, "Travel Time Forecasting and Dynamic Origin-Destination Estimation for Freeways Based on Bluetooth Traffic Monitoring," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2175, no. 1, pp. 19–27, Jan. 2010, doi: 10.3141/2175-03.

[12] E. Cascetta, "Estimation of trip matrices from traffic counts and survey data: A generalized least squares estimator," *Transp. Res. Part B Methodol.*, vol. 18, no. 4–5, pp. 289–299, Aug. 1984, doi: 10.1016/0191-2615(84)90012-2.

[13] J. Zhao, A. Rahbee, and N. H. M. Wilson, "Estimating a Rail Passenger Trip Origin-Destination Matrix Using Automatic Data Collection Systems," *Comput. Civ. Infrastruct. Eng.*, vol. 22, no. 5, pp. 376–387, Jul. 2007, doi: 10.1111/j.1467-8667.2007.00494.x.

[14] X. Zhou and G. F. List, "An Information-Theoretic Sensor Location Model for Traffic Origin-Destination Demand Estimation Applications," *Transp. Sci.*, vol. 44, no. 2, pp. 254–273, May 2010, doi: 10.1287/trsc.1100.0319.

[15] S. Kinugasa, T. Izumi, and Y. Nakatani, "Evaluation of a Support System for Large Area Tourist Evacuation Guidance: Kyoto Simulation Results," in *Lecture Notes in Geoinformation and Cartography*, vol. 0, Springer, Berlin, Heidelberg, 2013, pp. 309–315, doi: 10.1007/978-3-642-33218-0_22.

[16] S. Kinugasa, T. Izumi, and Y. Nakatani, "Evaluation of a support system for large area tourist evacuation guidance: Kyoto simulation results," *6th Int. Conf. Soft Comput. Intell. Syst. 13th Int. Symp. Adv. Intell. Syst. SCIS/ISIS 2012*, pp. 440–445, 2012, doi: 10.1109/SCIS-ISIS.2012.6505119.

[17] N. Emori, T. Izumi, and Y. Nakatani, "A Support System for Developing Tourist Evacuation Guidance," in *Transactions on Engineering Technologies*, Singapore: Springer Singapore, 2016, pp. 15–28, doi: 10.1007/978-981-10-0551-0_2.

[18] B. Ben Moshe, Y. Hadas, and H. Levi, "Energy-Efficient Framework for Indoor and Outdoor Tracking of Public Transit Passengers Using Bluetooth-Enabled Devices," *Trid*, 2014. [Online]. Available at: https://trid.trb.org/View/1288331.

[19] A. Bensky, *Wireless positioning technologies and applications*. Artech House, 2016.

[20] P. Mirowski, T. K. Ho, Saehoon Yi, and M. MacDonald, "SignalSLAM: Simultaneous localization and mapping with mixed WiFi, Bluetooth, LTE and magnetic signals," in *International Conference on Indoor Positioning and Indoor Navigation*, Oct. 2013, pp. 1–10, doi: 10.1109/IPIN.2013.6817853.

[21] Y. Yoshimura *et al.*, "An Analysis of Visitors' Behavior in the Louvre Museum: A Study Using Bluetooth Data," *Environ. Plan. B Plan. Des.*, vol. 41, no. 6, pp. 1113–1131, Dec. 2014, doi: 10.1068/b130047p.

[22] O. E. Nahum, G. Wachtel, and Y. Hadas, "Planning Tourists Evacuation Routes with Minimal Navigation Errors," *Transp. Res. Procedia*, vol. 47, pp. 235–242, Jan. 2020, doi: 10.1016/j.trpro.2020.03.094.

[23] G. Wachtel, J.-D. Schmöcker, Y. Hadas, Y. Gao, O. E. Nahum, and B. Ben-Moshe, "Planning for tourist urban evacuation routes: A framework for improving the data collection and evacuation processes," *Environ. Plan. B Urban Anal. City Sci.*, vol. 48, no. 5, pp. 1108–1125, Jun. 2021, doi: 10.1177/2399808321994575.

[24] Z. Wang and G. Jia, "Simulation-Based and Risk-Informed Assessment of the Effectiveness of Tsunami Evacuation Routes Using Agent-Based Modeling: A Case Study of Seaside, Oregon," *Int. J. Disaster Risk Sci.*, vol. 13, no. 1, pp. 66–86, Feb. 2022, doi: 10.1007/s13753-021-00387-x.

[25] X. Zhao, W. Xu, Y. Ma, L. Qin, J. Zhang, and Y. Wang, "Relationships Between Evacuation Population Size, Earthquake Emergency Shelter Capacity, and Evacuation Time," *Int. J. Disaster Risk Sci.*, vol. 8, no. 4, pp. 457–470, Dec. 2017, doi: 10.1007/s13753-017-0157-2.

[26] N. Shiwakoti, R. Tay, P. Stasinopoulos, and P. J. Woolley, "Likely behaviours of passengers under emergency evacuation in train station," *Saf. Sci.*, vol. 91, pp. 40–48, Jan. 2017, doi: 10.1016/j.ssci.2016.07.017.

[27] O. E. Nahum, Y. Hadas, R. Rossi, M. Gastaldi, and G. Gecchele, "Network Design Model with Evacuation Constraints Under Uncertainty," *Transp. Res. Procedia*, vol. 22, pp. 489–498, Jan. 2017, doi: 10.1016/j.trpro.2017.03.066.

[28] V. Zyryanov and A. Feofilova, "Simulation of Evacuation Route Choice," *Transp. Res. Procedia*, vol. 20, pp. 740–745, Jan. 2017, doi: 10.1016/j.trpro.2017.01.119.

[29] M. N. Jat and R. A. Rafique, "Mass-Casualty Distribution for Emergency Healthcare: A Simulation Analysis," *Int. J. Disaster Risk Sci.*, vol. 11, no. 3, pp. 364–377, Jun. 2020, doi: 10.1007/s13753-020-00260-3.

[30] Y. Hadas, R. Rossi, M. Gastaldi, C. Pellegrino, M. A. Zanini, and C. Modena, "Optimal Critical Infrastructure Retrofitting Model for Evacuation Planning," *Transp. Res. Procedia*, vol. 10, pp. 714–724, Jan. 2015, doi: 10.1016/j.trpro.2015.09.025.

[31] I. Miller, R. Kossik, and C. Voss, "General requirements for simulation models in waste management," in *WM'03 Conference*, 2003, pp. 1–12, [Online]. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.123.8163&rep=rep1&type=pdf.

[32] Y. Hadas and A. Laor, "Network design model with evacuation constraints," *Transp. Res. Part A Policy Pract.*, vol. 47, pp. 1–9, Jan. 2013, doi: 10.1016/J.TRA.2012.10.027.

[33] L. D. Han, F. Yuan, and T. Urbanik, "What Is an Effective Evacuation Operation?," *J. Urban Plan. Dev.*, vol. 133, no. 1, pp. 3–8, Mar. 2007, doi: 10.1061/(ASCE)0733-9488(2007)133:1(3).

[34] E. Bakhshian and B. Martinez-Pastor, "Evaluating human behaviour during a disaster evacuation process: A literature review," *J. Traffic Transp. Eng. (English Ed.*, vol. 10, no. 4, pp. 485–507, Aug. 2023, doi: 10.1016/j.jtte.2023.04.002.

[35] M. Kinateder *et al.*, "Social influence on route choice in a virtual reality tunnel fire," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 26, no. PART A, pp. 116–125, Sep. 2014, doi: 10.1016/j.trf.2014.06.003.

[36] S. A. F. Syed Abdul Rahman, K. N. Abdul Maulud, B. Pradhan, S. N. A. Syed Mustorpha, and A. I. Che Ani, "Impact of evacuation design parameter on users' evacuation time using a multi-agent simulation," *Ain Shams Eng. J.*, vol. 12, no. 2, pp. 2355–2369, Jun. 2021, doi: 10.1016/j.asej.2020.12.001.

[37] D. Amores, E. Tanin, and M. Vasardani, "A proactive route planning approach to navigation errors," *Int. J. Geogr. Inf. Sci.*, vol. 35, no. 6, pp. 1094–1130, Jun. 2021, doi: 10.1080/13658816.2020.1820508.

[38] M. Kobes, I. Helsloot, B. de Vries, and J. G. Post, "Building safety and human behaviour in fire: A literature review," *Fire Saf. J.*, vol. 45, no. 1, pp. 1–11, Jan. 2010, doi: 10.1016/j.firesaf.2009.08.005.

[39] K. Liu, Y. Ma, M. Chen, K. Wang, and K. Zheng, "A survey of crowd evacuation on passenger ships: Recent advances and future challenges," *Ocean Eng.*, vol. 263, p. 112403, Nov. 2022, doi: 10.1016/j.oceaneng.2022.112403.

[40] C. Chen, A. Mostafizi, H. Wang, D. Cox, and L. Cramer, "Evacuation behaviors in tsunami drills," *Nat. Hazards*, vol. 112, no. 1, pp. 845–871, May 2022, doi: 10.1007/s11069-022-05208-y.

[41] M. Haghani and M. Yazdani, "How simple behavioural modifications can influence evacuation efficiency of crowds: Part 2. Physical movement of individuals," *Transp. Res. Part C Emerg. Technol.*, vol. 166, p. 104762, Sep. 2024, doi: 10.1016/j.trc.2024.104762.

[42] M. Kutz, *Handbook of Transportation Engineering*, 2nd ed., vol. II. 2011.

[43] X. Ji, "Models and algorithm for stochastic shortest path problem," *Appl. Math. Comput.*, vol. 170, no. 1, pp. 503–514, Nov. 2005, doi: 10.1016/j.amc.2004.12.015.

[44] A. Madkour, W. G. Aref, F. U. Rehman, M. A. Rahman, and S. Basalamah, "A Survey of Shortest-Path Algorithms," *ArXiv*, pp. 1–26, 2017. [Online]. Available at: https://arxiv.org/pdf/1705.02044.

[45] P. Jaillet, “Shortest path problems with node failures,” *Networks*, vol. 22, no. 6, pp. 589–605, Oct. 1992, doi: 10.1002/net.3230220607.

[46] A. P. Riascos and J. L. Mateos, “Random walks on weighted networks: a survey of local and non-local dynamics,” *J. Complex Networks*, vol. 9, no. 5, Sep. 2021, doi: 10.1093/comnet/cnab032.

[47] A. P. Riascos, D. Boyer, P. Herringer, and J. L. Mateos, “Random walks on networks with stochastic resetting,” *Phys. Rev. E*, vol. 101, no. 6, p. 062147, Jun. 2020, doi: 10.1103/PhysRevE.101.062147.

[48] K. Sabashi, B. Ben-Moshe, J.-D. Schmöcker, Y. Hadas, and S. Nakao, “Simulation of tourists’ wayfinding during evacuation based on experiments in Kyoto,” *Transp. Res. Procedia*, vol. 62, pp. 640–647, Jan. 2022, doi: 10.1016/j.trpro.2022.02.079.

[49] J. Liu, A. K. Singh, A. Wunderlich, K. Gramann, and C.-T. Lin, “Redesigning navigational aids using virtual global landmarks to improve spatial knowledge retrieval,” *npj Sci. Learn.*, vol. 7, no. 1, p. 17, Jul. 2022, doi: 10.1038/s41539-022-00132-z.

[50] S. Vaez, M. Burke, and R. Yu, “Visitors’ wayfinding strategies and navigational aids in unfamiliar urban environment,” *Tour. Geogr.*, vol. 22, no. 4–5, pp. 832–847, Oct. 2020, doi: 10.1080/14616688.2019.1696883.

[51] A. Wunderlich and K. Gramann, “Landmark-based navigation instructions improve incidental spatial knowledge acquisition in real-world environments,” *J. Environ. Psychol.*, vol. 77, p. 101677, Oct. 2021, doi: 10.1016/j.jenvp.2021.101677.

[52] M. Balmer, M. Rieser, K. Meister, D. Charypar, N. Lefebvre, and K. Nagel, *MATSim-T: Architecture and Simulation Times*. IGI Global Scientific Publishing, 2009, doi: 10.4018/978-1-60566-226-8.ch003.

[53] K. W. Axhausen, *The Multi-Agent Transport Simulation MATSim*. Ubiquity Press, 2016, doi: 10.5334/baw.

[54] C. Zhuge, M. Bithell, C. Shao, X. Li, and J. Gao, “An improvement in MATSim computing time for large-scale travel behaviour microsimulation,” *Transportation (Amst).*, vol. 48, no. 1, pp. 193–214, Feb. 2021, doi: 10.1007/s11116-019-10048-0.

[55] A. M. Pereira, A. E. Dingil, O. Přibyl, V. Myška, J. Vorel, and M. Kříž, “An Advanced Travel Demand Synthesis Process for Creating a MATSim Activity Model: The Case of Ústí nad Labem,” *Appl. Sci.*, vol. 12, no. 19, p. 10032, Oct. 2022, doi: 10.3390/app121910032.

[56] H. Yang, E. Wong, H. Davis, and J. Y. J. Chow, “A co-simulation system that integrates MATSim with a set of external fleet simulations,” *Simul. Model. Pract. Theory*, vol. 134, p. 102957, Jul. 2024, doi: 10.1016/j.simpat.2024.102957.

[57] D. Alvarez Castro, A. Ford, P. James, R. Palacín, and D. Ziemke, “A MATSim model methodology to generate cycling-focused transport scenarios in England,” *J. Urban Mobil.*, vol. 5, p. 100078, Jun. 2024, doi: 10.1016/j.urbmob.2024.100078.

[58] A. Ficara, M. Fazio, A. Celesti, and M. Villari, “Design and Analysis of a MATSim Scenario from Open Data: The Case of Messina,” *Authorea Preprints*. Authorea, pp. 1–10, Sep. 05, 2024, doi: 10.36227/techrxiv.171436065.55682185/v3.

[59] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algrithms, 3rd Edition (The MIT Press)*, 3rd ed. 2009.

[60] G. Kootstra, “Selection of Landmarks for Visual Landmark Navigation,” *Order A J. Theory Ordered Sets Its Appl.*, no. September, pp. 1–73, 2002, [Online]. Available at: http://www.ai.rug.nl/nl/afstuderen/msc-theses/msc-thesis-gert-kootstra-2002.pdf.

[61] M. A. Zanini, C. Pellegrino, R. Rossi, M. Gastaldi, and C. Modena, “A probabilistic approach in estimating optimal evacuation scenarios for seismic emergency management,”.

[62] O. E. Nahum, Y. Hadas, M. Zanini, C. Pellegrino, R. Rossi, and M. Gastaldi, “Stochastic Multi-Objective Evacuation Model Under Managed and Unmanaged policies,” *Transp. Res. Procedia*, vol. 27, pp. 728–735, Jan. 2017, doi: 10.1016/j.trpro.2017.12.156.

[63] S. Santarelli, G. Bernardini, E. Quagliarini, and M. D'Orazio, "New Indices for the Existing City-Centers Streets Network Reliability and Availability Assessment in Earthquake Emergency," *Int. J. Archit. Herit.*, vol. 12, no. 2, pp. 153–168, Feb. 2018, doi: 10.1080/15583058.2017.1328543.

[64] H. Mousa *et al.*, "The Role of Urban Farming in Revitalizing Cities for Climate Change Adaptation and Attaining Sustainable Development: Case of the City of Conegliano, Italy," in *Green Buildings and Renewable Energy*, Springer, Cham, 2020, pp. 545–577, doi: 10.1007/978-3-030-30841-4_40.