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Smart city solutions: internet of things-enabled ambulances for enhanced post-earthquake resilience in Morocco

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ABSTRACT

Disasters such as earthquakes pose severe threats to sustainable urban development, causing loss of life, infrastructure collapse, and long-term disruption. In the critical first hours after an earthquake, delays in emergency response significantly reduce survival chances for vulnerable populations. This paper proposes an integrated framework that leverages internet of things (IoT)-enabled ambulances, geographic information systems (GIS), and optimization algorithms to enhance post-earthquake emergency response. The framework addresses two key challenges: i) optimal allocation of ambulances under resource constraints and ii) dynamic routing in disrupted road networks. Using real data from the 2023 Al Haouz earthquake in Morocco, the study compares deterministic approaches (Dijkstra, A*) with metaheuristics (particle swarm optimization (PSO), ant colony optimization (ACO), and Tabu Search (TS)). Results show that PSO reduced ambulance requirements by 40% while rescuing more citizens, and ACO achieved the highest route reliability (0.96). These findings demonstrate the practical applicability of IoT-enabled smart ambulances in improving resilience, efficiency, and equity in urban disaster management.

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1. INTRODUCTION

Earthquakes rank among the most devastating natural disasters, with consequences that extend far beyond the immediate moment of impact. They result in catastrophic loss of life, enormous economic harm, and lasting disruptions to the sustainable urban development of the affected regions [1], [2]. Beyond physical destruction, earthquakes often weaken social and infrastructural systems, amplifying vulnerability in already fragile communities [3], [4]. In the critical first few hours after an earthquake, the chances of survival for the most vulnerable populations particularly children, the elderly, and individuals with chronic conditions dwindle significantly if emergency responses are delayed [5], [6]. In such circumstances, traditional emergency response systems, which often rely on static protocols and limited situational awareness, prove inadequate [7], [8]. These challenges underscore the urgent need for intelligent and adaptive systems that can provide rapid, reliable, and flexible emergency response in highly disrupted urban settings [9], [10].

The internet of things (IoT) has emerged as a key enabler in disaster management. IoT-based technologies have been the subject of numerous studies, focusing on areas such as real-time patient monitoring, traffic management for emergency vehicles, and post-disaster environmental data collection [11]-[15]. By enabling the capture and transmission of critical data, IoT accelerates decision-making processes and enhances collaboration among different actors, including emergency responders, hospitals, and local authorities [16], [17]. In parallel, optimization techniques have been widely applied to ambulance triage and routing problems. These methods range from traditional deterministic approaches, such as shortest-path algorithms, to advanced metaheuristics capable of handling large, complex, and uncertain problem spaces [18]-[22]. Together, IoT and optimization represent complementary tools that can transform emergency response systems from reactive to proactive and adaptive [23], [24].

Despite these advancements, significant gaps remain. Many studies are restricted to controlled simulations, lacking validation with real-world disaster data [25], [26]. Integrated solutions that simultaneously incorporate IoT, GIS, and optimization methods are still rare [27], [28]. Moreover, few approaches take into account the true complexities of post-earthquake realities, which involve closed or blocked road networks, heavily damaged infrastructure, and severely limited medical and logistical resources [29]. These factors directly affect the speed, efficiency, and effectiveness of rescue operations. The recent Al Haouz earthquake in Morocco highlighted these challenges in stark detail, exposing weaknesses in existing systems and underscoring the urgent need for more resilient, adaptive, and data-driven approaches to disaster management [30].

In consideration of these aspects, this paper introduces an integrated framework designed to enhance urban resilience through the use of IoT-enabled smart ambulances. The framework leverages real-time IoT data streams, geographic information systems (GIS)-based spatial information, and a range of optimization techniques to address both ambulance allocation and dynamic routing challenges in disrupted environments. The main contributions of this work are summarized as follows:

- The design of a comprehensive framework that integrates IoT, GIS, and optimization to improve post-earthquake urban resilience and emergency response efficiency.
- A comparative evaluation of multiple optimization and routing algorithms, encompassing both deterministic and metaheuristic approaches, for dynamic ambulance allocation and routing.
- Validation of the proposed framework using primary data from the 2023 Moroccan earthquake, demonstrating its feasibility, adaptability, and practical relevance in a real-world context.

The remainder of this paper is organized as follows. Section 2 present related works. Section 3 details the methodology, including the system architecture, data description, and algorithms employed. Section 4 presents the experimental results and provides a critical discussion of their implications. Finally, section 5 concludes the paper and outlines potential directions for future research.

2. RELATED WORKS

The literature on disaster management highlights the role of emerging technologies such as the IoT, GIS, and optimization algorithms in strengthening urban resilience. However, existing studies often remain limited to simulations, lack integration across domains, or fail to consider real-world post-earthquake complexities. This section reviews prior works in three categories: i) IoT-enabled ambulances and patient monitoring, ii) GIS-based disaster routing, and iii) optimization approaches for emergency response.

IoT has been widely applied in healthcare for real-time monitoring of patients' vital signs, including heart rate, oxygen saturation, and blood pressure. Studies such as [15], [24] proposed smart ambulance systems (SAS) where vital signs are transmitted directly to hospitals for early intervention. Other works integrated IoT with cloud platforms and mobile applications to assist paramedics in identifying the nearest hospitals and available specialists [17], [31]. While these contributions demonstrate the potential of IoT in emergency medical services, they primarily focus on patient monitoring and do not address the challenges of ambulance allocation and routing in disaster-stricken areas.

GIS has been recognized as a critical tool in disaster management, providing spatial insights into road networks, hospital locations, shelters, and population density. Works such as [27], [28] demonstrated the usefulness of GIS in identifying accessible evacuation routes and optimizing resource deployment in congested cities. Similarly, recent studies emphasized GIS integration with IoT for post-disaster situational awareness and ambulance routing [32]. However, these studies often neglect the adaptive reallocation of ambulances under rapidly evolving conditions, particularly when road networks are blocked or severely damaged.

Optimization algorithms have been extensively studied for resource allocation and routing problems. Deterministic approaches, including Dijkstra and A*, provide efficient shortest-path solutions but struggle under dynamic and uncertain conditions. Metaheuristic methods such as particle swarm optimization (PSO), ant colony optimization (ACO), simulated annealing (SA), and Tabu Search (TS) have demonstrated robustness in solving complex optimization problems [20], [33]. Recent works in logistics and smart city applications [25], [26] confirm their ability to handle large-scale, uncertain environments. Nevertheless, their adoption in post-disaster ambulance management remains scarce, and most applications lack real-world validation.

From this review, three gaps emerge: i) IoT-enabled ambulance studies often remain limited to patient monitoring without addressing routing optimization, ii) GIS-based approaches provide spatial awareness but fail to integrate adaptive allocation mechanisms, and iii) optimization techniques are rarely combined with IoT and GIS in real-world disaster contexts. To the best of our knowledge, no existing framework integrates IoT, GIS, and optimization while being validated with primary data from a real earthquake scenario. This gap is addressed in the present study, which proposes a comprehensive IoT-enabled ambulance framework evaluated using data from the 2023 Al Haouz earthquake in Morocco.

3. METHOD

Proposed a framework that amalgamates data streams from the IoT, GIS-based spatial information and optimization algorithms for post-earthquake emergency response. The method includes system architecture, ambulance distribution optimization, and dynamic routing strategies. The parts that make up the method are: The following sections outline in detail each stage to ensure clarity, rigor, and reproducibility.

3.1. System architecture

Figure 1 shows the general architecture of the suggested IoT-enabled SAS, which also shows how the data acquisition, processing, and optimization layers interact.

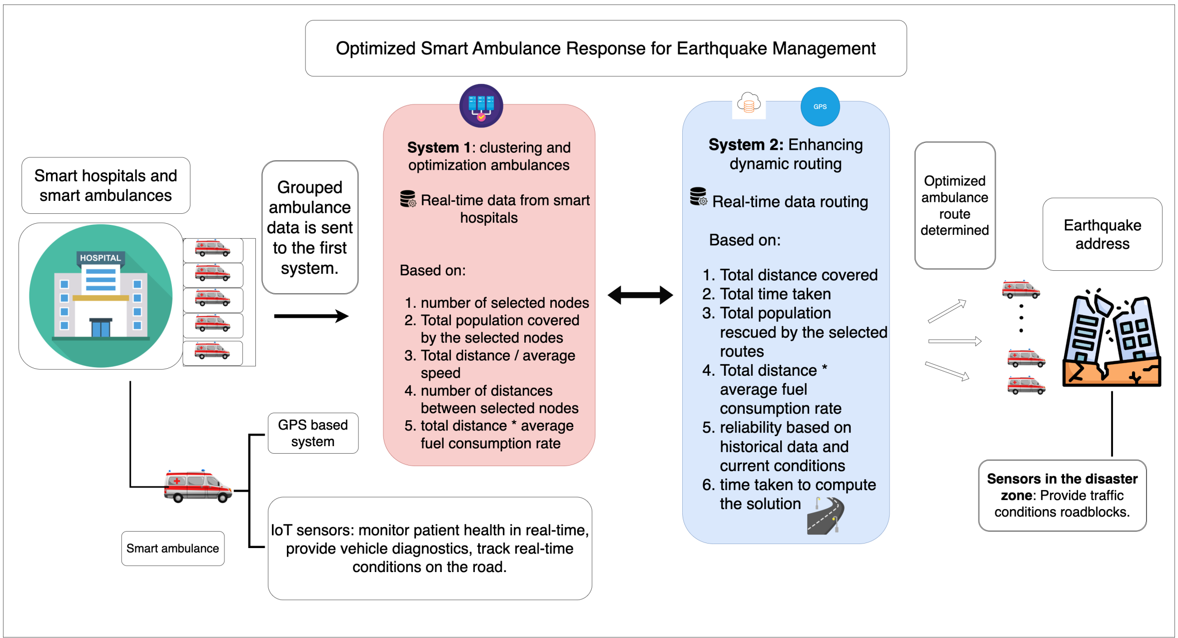

Figure 1. Optimized SAS architecture with three layers

The architecture is designed around three interconnected layers that ensure the continuous flow of data, analysis, and optimization:

- Data layer: this layer collects heterogeneous inputs from IoT devices, including real-time traffic sensors embedded in roads, GPS-equipped ambulances transmitting geolocation data, and environmental sensors monitoring damage levels to urban infrastructure. It also ingests contextual information such as weather conditions and seismic aftershocks, which may further disrupt mobility.
- Processing layer: at this stage, raw IoT data are integrated with GIS-based maps that contain road networks, hospital locations, shelters, and population density. Data cleaning, feature extraction, and normalization are

performed to harmonize information. The processing layer builds a unified decision-support environment where blocked or damaged routes are dynamically updated and urgency levels are adjusted based on population exposure.
- Optimization layer: this layer applies intelligent algorithms to allocate ambulances and compute adaptive routes under disrupted conditions. It continuously receives feedback from the data and processing layers, allowing it to adapt to new blockages, congestion, or demand surges.

This layered design ensures that real-time information directly informs decision-making processes, enabling adaptive responses to rapidly evolving post-disaster conditions and minimizing delays in medical intervention.

3.2. Data description

Two datasets simulate the post-earthquake urban environment:
- transport-nodes.csv: includes node IDs, GPS coordinates, type of node (hospital, intersection, or residential area), and local population estimates. Each node is assigned a weight that reflects urgency and vulnerability (e.g., elderly populations receive higher priority).
- transport-relationships.csv: encodes links between nodes, including distance, travel time, and road status (open, blocked, or damaged). Additional attributes such as fuel consumption (FC) and slope difficulty were incorporated to reflect real-world travel constraints in mountainous areas.

Preprocessing steps included: i) imputing or discarding missing values, ii) assigning high penalty costs to blocked roads to discourage their selection during optimization, and iii) normalizing population weights to reflect relative urgency across the network. These steps guarantee that the input data represent realistic post-disaster conditions.

The dataset used in this study consists of 10 nodes, which represent hospitals, road intersections, and residential areas, are connected by 59,780 road segments. Every road segment is associated with a record in the transport-relationships.csv file, whereas every node is defined in the transport-nodes.csv file. The region affected by the Al Haouz earthquake, including Marrakech and its environs, is the focus of the geographic coverage. Road disruptions, emergency accessibility conditions, and post-earthquake mobility constraints can all be modeled. Because each node represents an aggregated critical location (such as a hospital, residential cluster, or major intersection) rather than individual street-level points, it is crucial to note that the number of nodes is purposefully limited. While maintaining the crucial operational and spatial features needed for post-earthquake ambulance allocation and routing analysis, this abstraction lowers computational complexity. No personally identifiable information or patient data will be used in this study. This study uses aggregated and anonymized population-related data. Because the study only uses non-sensitive, publicly accessible, or simulated data, it complies with ethical research standards and data protection laws.

3.3. Use case 1: optimization of ambulance distribution

Efficient ambulance allocation is crucial to maximize citizen coverage when resources are scarce. To address this, several algorithms were implemented:
- Metaheuristics: genetic algorithm (GA), ACO, SA, PSO, and TS. Each algorithm was configured with population sizes, iteration limits, and convergence thresholds adapted from prior studies and fine-tuned experimentally for stability.
- Baseline: Knapsack problem, to provide a simple allocation benchmark.

Performance was evaluated using five metrics: number of ambulances required (NAR), number of citizens (NRC) rescued, average response time (TR), distance covered (DC), and FC. These indicators capture both operational efficiency and resource sustainability.

Algorithm 1 described the optimization procedure for allocating ambulances under constrained resources. It outlines the procedures for choosing the best ambulance locations based on operational effectiveness, accessibility, and population distribution. PSO, ACO, and TS were selected due to their proven effectiveness in addressing complex, dynamic, and resource-constrained optimization problems.

Due to its rapid convergence and effective global search capability, which enables swift decision-making under constrained resources, PSO is particularly well-suited for ambulance allocation. Because its pheromone-based learning mechanism enables continuous adaptation to blocked or disrupted road networks, ACO is well-suited to dynamic routing in post-earthquake environments. Because of its powerful local search capability, which effectively reduces the number of ambulances while maintaining high coverage levels, TS is included.

In real-world post-disaster scenarios with uncertainty and rapidly shifting network states, these metaheuristic algorithms offer greater resilience and adaptability than deterministic methods.

Algorithm 1. Optimization of ambulance distribution

Input: transport-nodes.csv, transport-relationships.csv, algorithm parameters
Output: NAR, NRC, TR, DC, FC

Step 1: Load and preprocess data (nodes, relationships, population)
Step 2: Apply optimization algorithms: Knapsack, GA, ACO, SA, PSO, TS
foreach *Algorithm* **do**
  Configure parameters (population size, max iterations, convergence threshold)
  Run optimization to select ambulance locations
Step 3: Evaluate metrics (NAR, NRC, TR, DC, FC)
Step 4: Compare results and select best-performing strategy

3.4. Use case 2: dynamic routing algorithm

Once ambulances are deployed, dynamic routing determines the most efficient paths under disrupted conditions. Algorithms tested included:

- Deterministic: Dijkstra, A*, and Bellman-Ford.
- Metaheuristics: GA, ACO, and SA. These were parameterized with appropriate crossover/mutation rates or pheromone decay factors, tuned for urban transport scenarios.

Evaluation metrics included: total distance covered (TDC), total travel time (TTT), NRC reached, FC, route reliability (RR, i.e., robustness to disruptions), and computational time (CT). Algorithm 2 describes the dynamic routing strategy used following ambulance deployment. It explains how, in post-earthquake environments, optimal routes are continuously calculated and updated in response to disturbed road conditions, traffic congestion, and changes in accessibility.

Algorithm 2. Dynamic routing algorithm

Input: transport-nodes.csv, transport-relationships.csv, algorithm parameters
Output: TDC, TTT, NRC, FC, RR, CT

Step 1: Load and preprocess network data
Step 2: Apply routing algorithms: Dijkstra, A*, Bellman-Ford, GA, ACO, SA
foreach *Algorithm* **do**
  Configure parameters (pheromone rate, mutation probability, etc.)
  Compute optimal routes under current network conditions
Step 3: Evaluate metrics (TDC, TTT, NRC, FC, RR, CT)
Step 4: Compare routing efficiency and robustness across algorithms

3.5. Reproducibility and research goals

The methodology is designed to be transparent and reproducible, enabling researchers to replicate the experiments with the provided datasets and algorithmic configurations. Each methodological choice data preprocessing, algorithm selection, parameter tuning, and evaluation metrics was explicitly documented. This ensures that the results can be independently verified and compared with future studies.

The methodological framework is also directly aligned with the overall research goal: to evaluate how IoT-enabled ambulance systems can enhance resilience and efficiency in post-earthquake emergency response. By combining real-world datasets, adaptive algorithms, and reproducibility principles, this study contributes both scientifically and practically to the field of disaster resilience. To make the proposed approach repeatable, all optimization algorithms were set up using well-defined parameters. The population size was varied between 30 and 50 individuals, depending on the optimization algorithm, and a maximum of 100 iterations. For the

ACO algorithm, the rate of pheromone evaporation was varied between 0.3 and 0.6. For the population-based optimization algorithms, the probability of mutation was varied between 0.05 and 0.1. The convergence criterion was considered either when the threshold was met or when the optimum number of iterations was reached. These parameters were determined by experiments based on the most frequently used combinations reported in the literature.

4. RESULTS AND DISCUSSION

4.1. Results

4.1.1. Evaluation of ambulance deployment strategies

Figure 2 and Table 1 summarize the performance of the optimization algorithms for ambulance allocation across several key metrics. The results show a clear performance gap between traditional and metaheuristic approaches. PSO and TS achieved the best trade-offs. PSO required only six ambulances to rescue 240 citizens within 3.8 hours, while TS reduced the number of ambulances to five and rescued 250 citizens. This highlights TS's superior capacity to optimize resource allocation with minimal fleet size. By contrast, the Knapsack baseline was the least efficient, requiring ten ambulances to rescue only 200 citizens, demonstrating the limitations of deterministic allocation when facing complex constraints. These observations can be attributed to the ability of metaheuristics to search the solution space and tackle different constraints concurrently. PSO performs optimization very efficiently with good exploitation and exploration properties, making it an appropriate choice when quick allocation is required and resources are not favoring expansion. TS also improves allocation efficiency by performing an extensive search process locally, thus reducing the fleet size without compromising coverage.

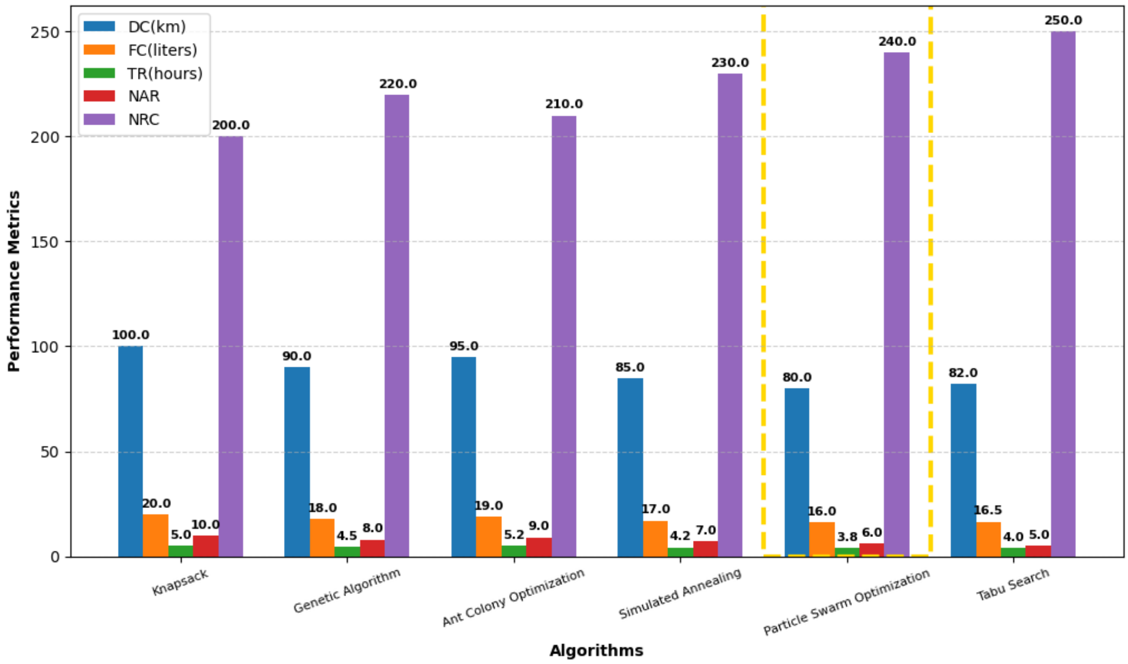

Figure 2. Optimization algorithms for ambulance distribution

Table 1. Performance metrics of ambulance distribution algorithms

Algorithm	NAR	NRC	TR (hours)	DC (km)	FC (liters)
Knapsack	10	200	5.0	100	20.0
GA	8	220	4.5	90	18.0
ACO	9	210	5.2	95	19.0
SA	7	230	4.2	85	17.0
PSO	6	240	3.8	80	16.0
TS	5	250	4.0	82	16.5

From a realistic point of view, these results have big implications when considering emergency response scenarios after earthquakes in Morocco, where ambulances are in short supply and mobility is restricted by damaged infrastructure. Reducing the number of ambulances needed while simultaneously maximizing the number of extracted civilians aids significantly in making such operations feasible and equitable at the affected locations on the city and rural levels.

4.1.2. Assessment of dynamic routing approaches

Table 2 and Figure 3 present the performance of routing algorithms under disrupted road conditions. As can be seen from Table 2 and the respective figures, ACO outperforms deterministic routing algorithms in terms of route reliability and adaptiveness. By using its pheromone-based learning mechanism, it continuously adapts to blocked or damaged road segments, which leads to more robust routing decisions under disrupted conditions.

Table 2. Performance metrics of routing algorithms

Algorithm	NRC	TDC (km)	TTT (hours)	FC (liters)	RR	CT (s)
Dijkstra	220	92	4.5	18.4	0.90	0.50
A*	230	85	4.0	17.0	0.95	0.40
Bellman-Ford	215	90	4.8	18.0	0.92	0.60
GA	225	88	4.2	17.6	0.93	0.45
ACO	235	84	3.9	16.8	0.96	0.35
SA	228	87	4.1	17.4	0.94	0.42

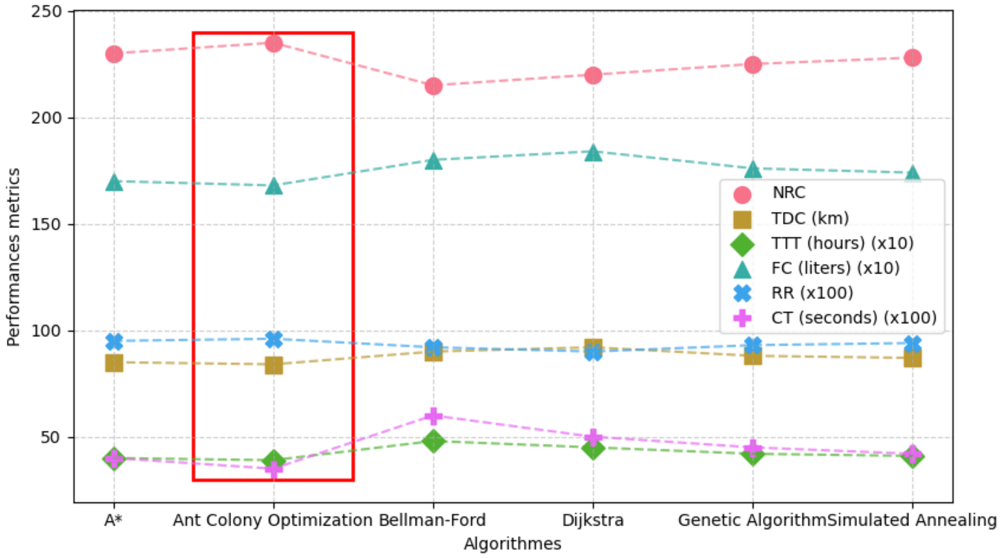

Figure 3. Optimization algorithms for dynamic routing

This adaptability is very relevant in post-earthquake scenarios such as the Al Haouz disaster, where road accessibility is often modified day by day because of debris, landslides, and infrastructure damages. This possibility of dynamic route reconfiguration makes ACO particularly suitable for emergency operations both in Moroccan urban centers and surrounding rural and mountainous areas.

From the above analysis, it is clear that the experimental results have confirmed the practicability and effectiveness of metaheuristic techniques when implemented in a post-earthquake situation. In the Moroccan environment, where there are variant road patterns, small-size roads, and inland settlements, the applications of PSO, TS, and ACO improve the efficiency of emergency response. The experimental outcome has verified the effectiveness of optimization techniques and IoT technologies in post-disaster situations for efficient decision-making.

Among the tested algorithms, ACO achieved the highest reliability (0.96) while rescuing 235 citizens in just 3.9 hours, outperforming deterministic methods such as Dijkstra and Bellman-Ford. A* also showed strong performance, balancing speed and simplicity with a 0.95 reliability rate. Metaheuristics, in general, achieved superior adaptability and resilience, with ACO in particular excelling in disrupted networks due to its pheromone-based reinforcement mechanism that enables rapid route reconfiguration.

4.2. Discussion

The results highlight the effectiveness of metaheuristic algorithms for both ambulance distribution and routing. PSO and TS proved highly efficient in resource allocation, while ACO consistently outperformed other routing methods under dynamic conditions. These findings align with previous studies that emphasized the robustness of swarm intelligence in uncertain environments [20], [21], [33]. Moreover, similar research on IoT-enabled emergency response confirmed that adaptive metaheuristics provide faster and more reliable coverage than deterministic methods [25], [26].

4.2.1. Practical implications

The Moroccan context provides an important validation of these results. The 2023 Al Haouz earthquake damaged infrastructure in mountainous regions and historic urban centers, creating conditions where deterministic algorithms such as Dijkstra fail to adapt to blocked roads. In contrast, ACO's pheromone-based adaptation allows real-time rerouting, while PSO flexibly identifies efficient ambulance deployment patterns. These capabilities are particularly critical in the narrow alleyways of Marrakech's medina and in remote High Atlas villages. Comparable approaches in India and Nepal have shown similar benefits when IoT and GIS are combined for emergency routing in congested urban areas [27].

4.2.2. Comparison with existing works

Compared with related frameworks that relied solely on simulations [15], [24], our approach integrates real earthquake data, demonstrating greater feasibility and contextual relevance. Furthermore, while previous studies focused either on ambulance routing or patient monitoring, the proposed framework provides a comprehensive solution that addresses both allocation and navigation challenges. Other works [12] emphasized IoT's potential in smart cities, but our study demonstrates its tangible impact in post-disaster contexts using real-world data.

4.2.3. Limitations and future work

Despite these promising results, several limitations remain:

- The simulations depend on partially observed datasets, which may not fully capture real post-disaster conditions. Future studies should include cross-validation against baseline emergency response data or expert evaluation to further confirm the robustness of our framework [29].
- Algorithm parameters were tuned experimentally, but further sensitivity analyses are required to assess robustness under different earthquake intensities and infrastructural damage scenarios.
- Ethical and operational considerations, such as prioritizing vulnerable groups (e.g., children, elderly, or persons with disabilities) and ensuring integration with national emergency protocols, were not explicitly modeled. These issues must be addressed before large-scale deployment [4].

Future work should include pilot testing with Moroccan municipalities, hybrid optimization approaches combining deterministic and metaheuristic methods, and scalability assessments in larger urban contexts.

Results of testing this framework in a qualitative manner under different disruption scenarios indicate that in the presence of higher disruption situations on the roads and level of congestions, deterministic Routing algorithms will be less effective with less adaptability abilities while the metaheuristically based algorithms will stay effective due to their continuous adaptive properties.

Regarding the issue of computational complexity and efficiency of computation, it is observed from execution times that these fall within manageable limits for real-time execution of emergency response activities. This is sufficiently optimal to enable frequent changes to routing and allocation without critical delays to these activities. As such, this proposed framework can be incorporated within currently operative emergency response and command centers to incorporate real-time IoT and GIS inputs for decision-making in post-earthquake rescue activities.

5. CONCLUSION

This study presented an integrated framework for enhancing post-earthquake urban resilience through IoT-enabled smart ambulances. The framework combines real-time IoT data, GIS-based spatial analysis, and optimization algorithms to address two key challenges: efficient ambulance allocation under resource constraints and adaptive routing in disrupted networks.

Based on experimental results, it is found that some of the proposed metaheuristics approaches such as PSO, TS, and ACO perform far better than the use of deterministic methods alone, as this will reduce the NAR for deployment, improve coverage and increase reliability of the routing, respectively. These findings also demonstrate the efficacy of adaptive.

Apart from the strictly technical findings measured via machine learning approaches most authors or papers see we also emphasize the capability of our framework (with all components) to be used by a possible intelligent agent (or human being).

Nonetheless, some limitations exist. The datasets were streamlined and observed partially. The algorithms require more sensitivity analysis to make them robust to different conditions. Before large-scale deployment, moral and practical aspects must be taken into account, particularly prioritizing the vulnerable and integrating into national emergency plans.

In the future, some of the research would include pilot studies in collaboration with local municipalities, integration of real-time data from emergency services, and formulation of different hybridisation strategies between deterministic and meta-heuristic methods. Extending the framework to other disaster contexts such as floods or wildfires, and assessing its scalability in larger metropolitan areas, will further strengthen its applicability.

Overall, the proposed approach contributes both scientifically and practically to building more resilient and adaptive emergency response systems in smart cities.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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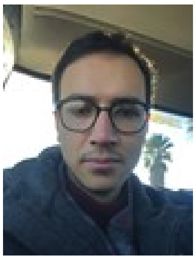

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