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Enhancing disaster management in smart cities through MCDM-AHP analysis amid 21st century challenges

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ABSTRACT: In the era of rapid urbanization and technological progress, smart cities offer a promising solution to multifaceted global challenges, leveraging advanced technologies to optimize resources and enhance the quality of life; however, this interconnectedness also exposes them to novel vulnerabilities, particularly in the face of natural and man-made disasters, necessitating inventive strategies to ensure resilience against cyber threats and extreme weather events. This article delves into the exploration of smart cities' diverse aspects and the categories of disasters they face, followed by an analysis of strategic mitigation approaches and their underlying criteria; it subsequently introduces the Multi-Criteria Decision-Making methodology, particularly Analytical Hierarchy Process (AHP), as a robust tool for systematic evaluation and prioritization of disaster management strategies in the increasingly complex landscape. The study's analysis of relative weights underscores the pivotal role of resilience enhancement and communication redundancy as primary considerations in evaluating disaster management strategies for smart cities, while other criteria such as accuracy and timeliness, scaleability and adaptability, cost-effectiveness, ethical and privacy considerations, and training and skill requirements assume varying degrees of importance in supporting roles, providing valuable insights into the decision-making process. The assessment of alternative strategies highlights their prioritization in effective disaster management for smart cities, with notable emphasis on citizen engagement and education, early warning systems, and data analytics; further strategies such as integrated communication systems, resilient infrastructure design, drones and robotics, artificial intelligence algorithms, and IoT-enabled sensors and monitoring exhibit varying degrees of significance, offering insights into their roles and potential contributions to disaster management strategies based on their weighted sums. This research has practical significance, guiding stakeholders like urban planners, policymakers, and disaster management professionals to enhance smart city resilience and prioritize strategies based on critical factors, ultimately enabling effective disaster management in smart cities amid 21st-century challenges.

KEYWORDS: 21st-Century energy transition challenges; analytical hierarchy process; disaster management; multi-criteria decision-making; smart cities

1. Introduction

1.1. Research motivation

In the 21st century, the world is witnessing an unprecedented wave of urbanization and technological advancement, giving rise to the concept of smart cities[1–3]. These urban centers, characterized by their integration of cutting-edge technologies and data-driven infrastructure, hold immense potential for improving the quality of life, sustainability, and efficiency of urban living[4]. However, as the complexity of these smart cities grows, so do the challenges they face, particularly in the realm of disaster management[5].

The accelerating pace of urbanization and the increasing reliance on interconnected systems have introduced novel vulnerabilities that smart cities must confront. From cyber-attacks targeting critical infrastructure[6] to the escalating frequency and intensity of natural disasters fueled by climate change[7–9], the resilience of smart cities is being tested on multiple fronts. These challenges necessitate innovative and adaptive disaster management strategies that can effectively safeguard lives, infrastructure, and the functioning of urban ecosystems.

1.2. Existing research and knowledge gaps

While significant research has been devoted to disaster management in traditional urban settings[10,11], the unique characteristics of smart cities demand a tailored and comprehensive approach. The integration of advanced technologies, real-time data analytics, and interconnected systems in smart cities presents both opportunities and complexities in disaster management. As such, there is a compelling need to explore and evaluate strategies that address the specific challenges posed by 21st-century urban environments.

1.3. Research questions and methodology

This research aims to fill a critical gap in the literature by providing a comprehensive exploration of disaster management in smart cities, spanning from understanding the smart city landscape and disaster types to evaluating strategies and applying analytical methods for decision-making. Specifically, this study addresses two research questions:

- What are the fundamental characteristics that define a smart city? What are the specific types of disasters that pose threats to smart cities?
- How can disaster management strategies in smart cities be effectively evaluated and prioritized using the Multi-Criteria Decision-Making (MCDM) technique, particularly the Analytical Hierarchy Process (AHP), considering key criteria such as resilience enhancement, communication redundancy, accuracy and timeliness, scalability and adaptability, cost-effectiveness, ethical and privacy considerations, and training and skill requirements?

The AHP is a structured method within MCDM that systematically evaluates and prioritizes alternatives by breaking down complex decisions into a hierarchical structure. It involves pairwise comparisons to assign relative importance or preference, generating matrices that quantify relationships. AHP uses mathematical calculations to derive weights for criteria and alternatives, resulting in a prioritized ranking. This process aids decision-makers in making informed choices by quantifying intricate considerations, making it a valuable tool for assessing disaster management strategies in smart cities and other intricate scenarios.

1.4. Practical implications

The practical implication of this research lies in its potential to guide urban planners, policymakers, and disaster management professionals in making informed decisions to fortify the resilience of smart cities. By elucidating the fundamental attributes of smart cities, identifying their vulnerability to various disaster types, and delineating key criteria for evaluating disaster management strategies, the study equips stakeholders with a comprehensive understanding of the multifaceted challenges at hand. Moreover, the application of the MCDM technique, specifically the AHP, provides a structured approach to assess and prioritize strategies based on critical factors such as resilience enhancement, communication redundancy, cost-effectiveness, and ethical considerations. Ultimately, this research empowers decision-makers to tailor effective disaster management approaches in smart cities, fostering a safer and more resilient urban environment in the face of 21st-century challenges.

1.5. Outline

After this introduction, which provides an overview of the research motivation (Section 1.1), existing research and knowledge gaps (Section 1.2), research questions and methodology (Section 1.3), and practical implications (Section 1.4), Section 2 presents the adapted methodology, specifically focusing on the MCDM-AHP framework. In Section 3, the results of the study are presented, while in Section 4.1 we provide implementation details and empirical findings to enhance comprehension of our approach's practicability and effectiveness. We also validate our approach through real-world smart city case studies, such as the recent earthquake in Morocco[12], illustrating its real-world applicability and practical implications. Section 4.2 highlights the advantages and limitations of our approach in comparison to traditional disaster management methods. Section 5 concludes the research and proposes future directions for further exploration.

2. Methodology

In this study, to evaluate disaster management strategies in smart cities based on multiple criteria, we use the Multi-Criteria Decision-Making Analytic Hierarchy Process (MCDM-AHP) method.

The Analytic Hierarchy Process (AHP) is a Multi-Criteria Decision-Making (MCDM) methodology developed by Saaty et al.[13,14]. It is widely used for decision-making and prioritization when dealing with complex problems involving multiple criteria and alternatives[15,16]. AHP involves a structured approach that decomposes a complex decision problem into a hierarchy of criteria and sub-criteria and then employs pairwise comparisons to derive relative weights for these elements[17,18].

The utilization of MCDM spans diverse domains owing to its capacity to address intricate decision challenges encompassing multiple criteria and options. MCDM has witnessed widespread application in various fields, such as identifying suitable regions for photovoltaic and concentrated solar power projects[19], evaluating onshore wind energy potential[20], assessing offshore wind energy feasibility[21], and exploring opportunities for offshore floating photovoltaic installations[22]. MCDM-AHP has found application in the identification of optimal cybersecurity solutions within smart grid environments, including integration with artificial intelligence, as exemplified in a recent research endeavor by Bouramdane et al.[23].

The theoretical framework of the AHP consists of the following steps[24,25]. First, we define the hierarchy or the decision problem by breaking it down into a hierarchy of criteria, sub-criteria, and alternatives. The hierarchy is organized from the most general level (the goal) to the most specific level (the alternatives) (**Figure 1**).

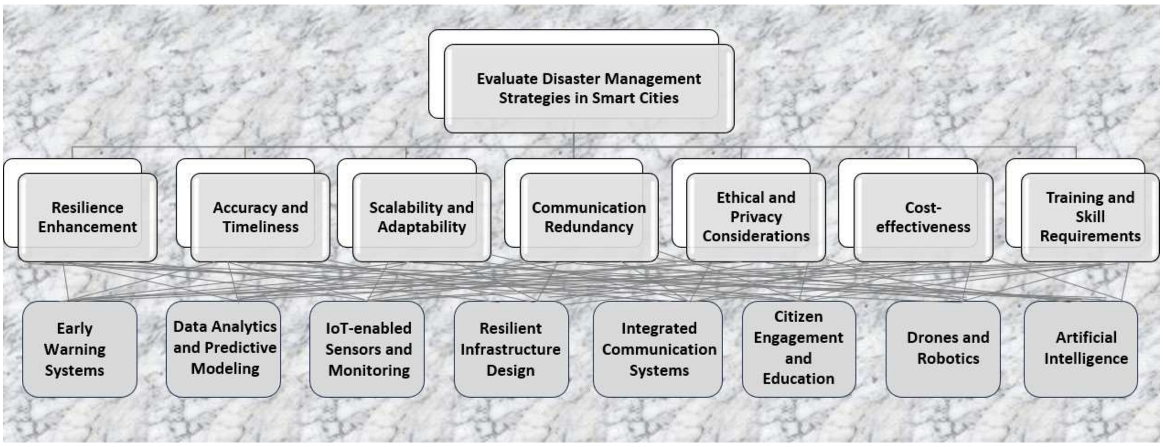

Figure 1. The hierarchical assessment framework for disaster management strategies in smart cities comprises multiple tiers: a higher-level over- arching objective, intermediary evaluation factors, and a lower level encompassing diverse alternatives. Source: Author's own elaboration.

Second, we conduct pairwise comparisons of elements at each level of the hierarchy to determine their relative importance or preference (equation (1)). A fundamental scale of values is used for comparisons, often ranging from 1 (equal importance) to 9 (extremely more important)[13]:

$$A = \begin{pmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \cdots & 1 \end{pmatrix}, \ a_{ij} = \frac{1}{a_{ji}}, a_{ii} = 1. \tag{1}$$

Third, we ensure the consistency of the pairwise comparison matrix by evaluating the consistency ratio (CR) or using other consistency measures. Inconsistent judgments might need to be revised.

Fourth, we calculate the principal eigenvector of each pairwise comparison matrix (Equation (2)). This eigenvector represents the relative weights of the elements in the matrix:

$$A\omega = \lambda\omega \tag{2}$$

where ω is the principal eigenvector of matrix A, and λ is the corresponding eigenvalue.

Then, we propagate the relative weights upward through the hierarchy, aggregating them at each level to calculate the overall weights of criteria and alternatives (equation (3)). For each level L of the hierarchy:

$$W_L = \frac{1}{n_L} \sum_{i=1}^{n_L} W_{Li} \tag{3}$$

where n_L is the number of elements at level L, and W_{Li} is the weight of element i at level L.

Finally, we calculate the priorities or scores of the alternatives by combining the weights of the criteria with the performance scores of alternatives on each criterion (equation (4)). For each alternative j:

$$P_j = \sum_L W_L \ PerformanceScore_{L_j} \tag{4}$$

Where $PerformanceScore_{L_j}$ is the performance score of alternative j on criterion L.

3. Results

In this section, we delve into a comprehensive exploration. First, we provide an insightful overview of smart cities (Section 3.1.1) and delve into the various types of disasters that can impact smart cities

(Section 3.1.2). Moving forward, we delve into disaster management strategies within smart cities (Section 3.2.1), meticulously examining the essential criteria that warrant consideration when evaluating these strategies (Section 3.2.2). Moreover, we illuminate how the potent Multi-Criteria Decision-Making (MCDM) method, specifically the Analytic Hierarchy Process (AHP), is harnessed to systematically evaluate both the criteria and strategies (Section 3.2.3), facilitating an informed decision-making process for enhancing disaster preparedness and response.

3.1. Comprehensive analysis: Smart city landscape and types of disasters in smart cities

3.1.1. Smart cities overview

Smart cities are urban areas that use data-driven technology (i.e., sensors, devices, etc.) and innovative solutions (i.e., real-time tracking of buses and trains, mobile applications for route planning, contactless payment systems, etc.) to improve the quality of life for residents, enhance sustainability by integrating eco-friendly practices (i.e., renewable energy sources[26,27], efficient waste and water management, green buildings, electric vehicle charging stations, smart street lighting), make informed decisions—about transportation, energy usage, public safety, healthcare, education, and access to information and services, optimize resource allocation, and enhance urban services. These cities leverage various technologies, including the Internet of Things (IoT) (i.e., connecting various objects to the internet), data analytics, artificial intelligence (AI), and connectivity, to create efficient and intelligent urban ecosystems. This enables real-time data collection, monitoring, and control of urban infrastructure and services[4].

Examples of practices frequently observed in smart cities include:

- **Smart Traffic Management**: using real-time data from sensors, cameras, and GPS systems to monitor traffic flow, predict congestion, and optimize traffic signal timings, helps reduce traffic jams and improve overall transportation efficiency[28,29].
- **Waste Management**: Installing smart bins with sensors that monitor their fill levels and notify waste management teams when they need emptying reduces unnecessary trips and optimizes collection routes[30,31].
- **Energy Management**: Deploying smart grids to monitor energy consumption and balance supply and demand more effectively leads to energy savings and reduces environmental impacts[32].
- **Smart Lighting**: Installing energy-efficient LED streetlights equipped with sensors that adjust brightness based on ambient light levels and human presence thereby reduces energy consumption and light pollution[33].
- **Environmental Monitoring**: Using data from sensors that measure air quality, noise levels, and other environmental factors in real-time helps identify pollution hotspots and develop strategies for improving urban air quality[34,35].
- **Smart Water Management**: Implementing IoT-enabled water sensors to monitor water usage, detect leaks, and manage irrigation systems more efficiently conserves water resources[36,37].
- **Emergency response**: Using sensors and data analytics to detect and respond to emergencies more swiftly, such as fires, earthquakes, or accidents, helps notify emergency services and citizens[38].
- **Citizen Engagement Platforms**: Developing digital platforms and mobile applications that allow citizens to report issues, provide feedback, participate in decision-making processes, and foster greater community engagement[39].
- **Smart Healthcare**: Implementing telemedicine solutions, wearable health devices, and digital health records enhances healthcare access and services for residents[40,41].

- **E-Governance**: Providing online services for tasks such as paying taxes, obtaining permits, and accessing government information makes administrative processes more efficient and convenient[42].
- **Smart Education**: Introducing digital learning tools, interactive classrooms, and online education platforms enhances the quality of education and promotes lifelong learning[43].
- **Smart Parks and Recreation**: Installing sensors in public spaces helps monitor usage, optimize maintenance schedules, and enhance safety in parks, playgrounds, and recreational facilities[44].
- **Public Safety**: Deploying surveillance cameras, gunshot detection systems, and predictive policing algorithms improves law enforcement and emergency response capabilities[45].
- **Digital Infrastructure**: Establishing high-speed internet connectivity and Wi-Fi hotspots throughout the city helps ensure equal access to digital services and information[46,47].

Smart cities can drive economic growth by fostering innovation, attracting technology companies, and creating new job opportunities in the technology and data analysis sectors[48].

Some well-known examples of smart cities include Singapore[49,50], Seoul (South Korea)[50], Barcelona (Spain)[51,52], Copenhagen (Denmark)[53], Dubai (United Arab Emirates)[51,52], Tokyo (Japan)[54], Toronto (Canada)[55], San Francisco (USA)[56], Amsterdam (Netherlands)[52], Songdo (South Korea)[57], Hong Kong (China)[58], Oslo (Norway)[59], Santander (Spain)[60], and Helsinki (Finland)[61]. Each of these cities has implemented various smart technologies to improve urban living.

3.1.2. Types of disaster in smart cities

Smart cities are designed to use technology, data analytics, and early warning systems to enhance resilience and response during various types of disasters. For instance, real-time monitoring, predictive modeling, and efficient communication can help authorities respond more effectively and provide timely assistance.

However, they can still face a range of disasters, both natural and man-made[5]. Some types of disasters that smart cities may face include:

- **Natural Disasters** such as heavy rainfall leading to flooding[7,62,63], earthquakes that can collapse buildings, hurricanes, and cyclones (i.e., high winds, heavy rainfall, and storm surges)[64], uncontrolled fires that cause air quality issues[8,9], prolonged periods of drought and water scarcity can impact water supply[65,66], agriculture[67,68], and overall quality of life[69].
- **Man-Made Disasters** such as cyberattacks (i.e., hacking and cyber incidents)[6], terrorist attacks, industrial accidents (i.e., chemical spills, explosions), large-scale fires, failures in essential infrastructures (i.e., power grids, water supply systems, or transportation networks), outbreaks of infectious diseases, and poor air quality due to pollution or other factors can pose risks to health, public safety, and the environment[69].
- **Climate Change-Related Disasters** such as sea-level rise—which can lead to coastal flooding and erosion[22], and heatwaves (i.e., extended periods of high temperatures)—which can impact public health, strain energy resources, and lead to heat-related illnesses[7,62,63]. Technological disasters, such as accidents at nuclear facilities and accidental releases of hazardous materials, can endanger public safety and require swift response.

3.2. Evaluating disaster management strategies in smart cities using MCDM-AHP

3.2.1. Disaster management strategies in smart cities

Disaster management strategies implemented in smart cities encompass a range of proactive and technology-driven approaches to mitigate, respond to, and recover from various types of disasters[70]. Key disaster management strategies in smart cities include:

1) **Early warning systems**: Smart cities use sensors and real-time monitoring to detect potential disasters, such as earthquake early warning (i.e., using seismic sensors to detect initial tremors and trigger automated alerts to residents, emergency services, and critical infrastructure systems) or flood monitoring (i.e., deploying water level sensors in flood-prone areas to provide real-time data and trigger evacuation alerts when water levels rise)[71].
2) **Data Analytics and Predictive Modeling**: Advanced data analytics help identify disaster patterns and predict potential risks. This information assists in resource allocation, decision-making, and proactive planning to reduce vulnerabilities. Notable instances comprise hurricane tracking and prediction (i.e., analyzing historical weather data and real-time satellite imagery to predict the path and intensity of hurricanes, enabling accurate evacuation planning) or heatwave prediction (i.e., using historical temperature data and weather forecasts to anticipate heatwaves and implement heat action plans to protect vulnerable populations)[72,73].
3) **IoT-enabled Sensors and Monitoring**: Deploying sensors across the city helps monitor critical infrastructure, environmental conditions, and emergency situations. Data from these sensors informs authorities about ongoing developments, enabling swift and informed responses. Prominent instances encompass air quality monitoring (i.e., installing air quality sensors throughout the city to continuously monitor pollution levels and provide health advisories during poor air quality episodes) or building structural health monitoring (i.e., equipping buildings with sensors to assess structural integrity during earthquakes or other seismic events)[74,75].
4) **Resilient Infrastructure Design**: Smart cities incorporate resilient urban planning and infrastructure design to withstand disasters. This includes flood-resistant infrastructure (i.e., constructing flood barriers, elevated roadways, and water drainage systems to mitigate flood damage and ensure continued functionality during and after heavy rainfall), and earthquake-resistant buildings[76].
5) **Integrated Communication Systems**: Smart cities establish robust communication networks that connect authorities, emergency services, and residents. Effective communication ensures coordinated responses and the dissemination of critical information. Key examples include emergency alert systems (i.e., implementing multi-channel communication platforms such as text messages, social media, or sirens to quickly disseminate critical information to residents and visitors during emergencies)[77].
6) **Citizen Engagement and Education**: Educating residents about disaster preparedness and response is crucial. Smart cities use digital platforms, mobile apps, and social media to provide information, guidelines, and updates to citizens. Prominent illustrations encompass emergency applications (i.e., developing mobile applications that provide real-time updates, evacuation routes, shelter locations, and safety tips to empower citizens to make informed decisions)[78].
7) **Drones and Robotics** such as search and rescue drones (i.e., deploying drones equipped with cameras and sensors to search for survivors in disaster-stricken areas and relay real-time data to response teams)[79].
8) **Artificial intelligence (AI) Algorithms**: Artificial intelligence (AI) plays a crucial role in managing disasters in smart cities by providing advanced capabilities for continued learning and improvement (i.e., AI algorithms can learn from past disaster responses and continuously improve strategies based on new data, enhancing future disaster management efforts), post-disaster recovery planning (i.e., AI can assist in analyzing data from post-disaster assessments to develop effective recovery and reconstruction plans, ensuring that resources are allocated efficiently), healthcare and medical response (i.e., AI-driven healthcare analytics can predict and man- age medical demand during disasters, optimize medical supply distribution, and aid in patient triage), public sentiment analysis

(i.e., AI can analyze social media and other data sources to gauge public sentiment, helping authorities understand public perceptions and concerns during disasters), communication and information sharing (i.e., Natural language processing and chatbots powered by AI can provide accurate and up-to-date in- formation to residents, answer their queries, and offer guidance during disasters), smart traffic management (i.e., AI-powered traffic management systems can dynamically adjust traffic signals, reroute vehicles, and optimize traffic flow to facilitate efficient evacuations and emergency response), real-time situational awareness (i.e., AI algorithms can process data from various sources, including sensors, social media, and news feeds, to provide decision-makers with real-time situational awareness and insights into evolving disaster scenarios), and predictive analysis and early warning systems (i.e., AI algorithms can analyze historical data and real-time information from various sources to predict the likelihood, intensity, and impact of disasters such as earthquakes, floods, and storms. In addition, AI-driven early warning systems can rapidly detect anomalies and trigger alerts, giving authorities and residents more time to prepare and respond)[80,81].

3.2.2. Key criteria

When evaluating disaster management strategies in smart cities, the following relevant criteria should be considered:

1) **Resilience Enhancement**: Assess the degree to which the strategy contributes to the resilience of smart city infrastructure against disasters, including its ability to withstand and recover from disruptions.
2) **Accuracy and Timeliness**: Evaluate the accuracy of early warning systems and the timeliness of alerts in providing advance notice of impending disasters, allowing for proactive measures.
3) **Scalability and Adaptability**: Determine whether the strategy can scale to handle different disaster scenarios and adapt to changing conditions, ensuring a comprehensive approach.
4) **Communication Redundancy**: Examine the redundancy and reliability of integrated communication systems, ensuring that critical information reaches relevant stakeholders during disasters.
5) **Ethical and Privacy Considerations**: Examine how the data collected and utilized by the strategy adheres to ethical standards and protects the privacy of individuals.
6) **Cost-effectiveness**: Evaluate the cost-effectiveness of implementing and maintaining the strategy in relation to the benefits gained in disaster prevention, response, and recovery.
7) **Training and Skill Requirements**: Consider the training and skill levels required for personnel to effectively implement and operate the strategy, ensuring successful execution during emergencies.

Considering these criteria holistically will facilitate a comprehensive evaluation of disaster management strategies in smart cities, enabling the selection of approaches that best align with the city's goals and priorities while ensuring effective disaster preparedness and response.

3.2.3. Pairwise comparison matrix, relative weights of criteria, weighted sum of alternatives

Within this section, we delve into the assessment of disaster management strategies in smart cities by subjecting them to a set of predetermined criteria, as detailed in Section 3.2.2. To facilitate this evaluation, we construct a pairwise comparison matrix (see **Table 1**), allowing us to discern the relative significance of each criterion when juxtaposed with others (as demonstrated in **Figure 2**). Leveraging these established relative weights, we proceed to calculate the cumulative weighted scores for each disaster management option (refer to **Figure 3**). This calculation yields an encompassing score that takes into account the pivotal role played by each criterion in the overall assessment.

Table 1. Matrix for pairwise comparison among criteria—Resilience Enhancement (C1), Accuracy and Timeliness (C2), Scalability and Adaptability (C3), Communication Redundancy (C4), Ethical and Privacy Considerations (C5), Cost-effectiveness (C6), and Training and Skill Requirements (C7)—to evaluate disaster management strategies in smart cities. We adopt a rating scale ranging from 1 to 9, wherein 1 denotes equivalent significance and 9 signifies markedly greater importance (as discussed in Section 2). It's important to note that this assessment is subjective and susceptible to variance based on individual viewpoints and preferences.

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	1	3	5	2	7	4	6
C2	1/3	1	3	1/2	5	2	4
C3	1/5	1/3	1	1/6	3	1	2
C4	1/2	2	6	1	9	5	8
C5	1/7	1/5	1/3	1/9	1	1/4	1/6
C6	1/4	1/2	1	1/5	4	1	3
C7	1/6	1/4	1/2	1/8	6	1/3	1

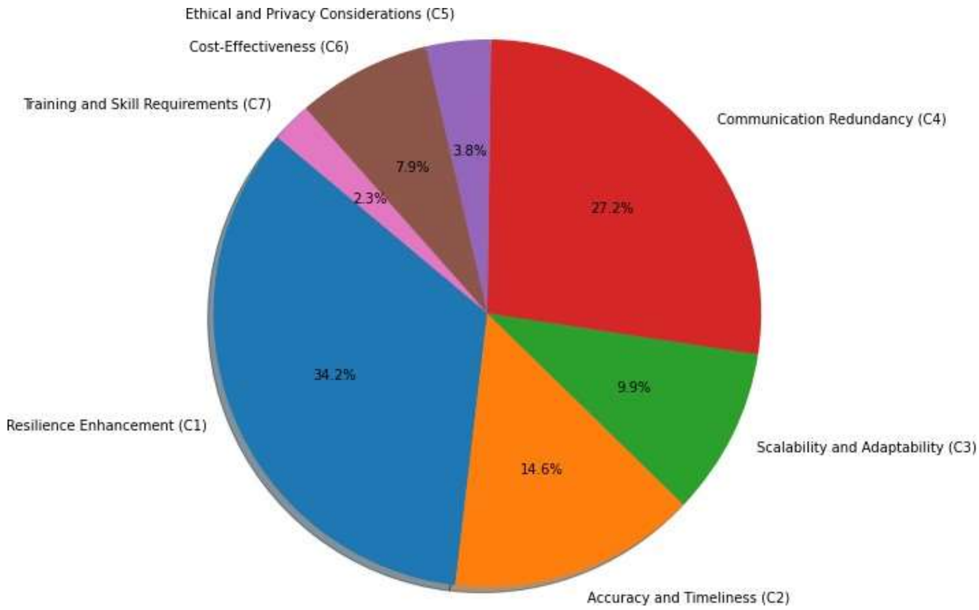

Figure 2. Criterion Weights (CWs), representing the priority or significance allotted to each criterion during the assessment of disaster management strategies in smart cities. These weights elucidate the relative importance of each criterion in shaping the comprehensive efficacy of the alternatives. Source: Own Elaboration based on Section 2.

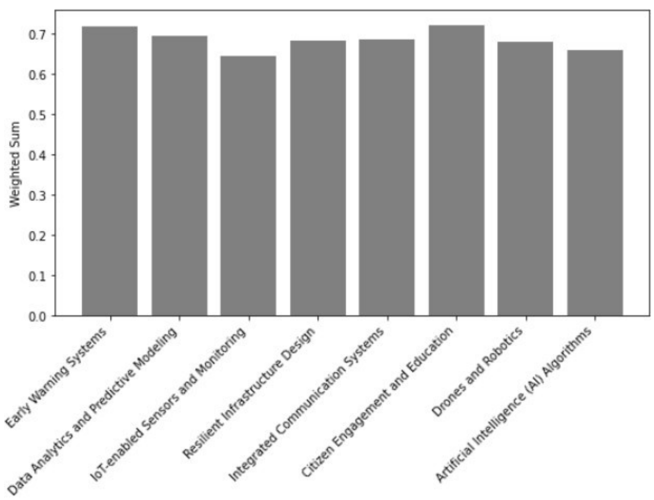

Figure 3. Aggregate Weighted Scores for Each Alternative. Elevated weighted sums correspond to superior overall performance. Source: Own Elaboration based on Section 2.

Based on the calculated relative weights (**Figure 2**), we find that resilience enhancement (weight: 34.24%) has the highest weight, indicating that enhancing the resilience of smart cities is considered a top priority in evaluating disaster management strategies. Communication redundancy (Weight: 27.19%) is assigned a relatively high weight, indicating its significant role in disaster management strategies for smart cities.

Accuracy and Timeliness (Weight: 14.57%) criterion has a moderate weight, suggesting that while accuracy and timeliness are important, they are not as crucial as resilience enhancement. Similar to accuracy and timeliness, scalability and adaptability (Weight: 9.90%) hold a moderate level of importance in the evaluation process. Cost-effectiveness (Weight: 7.93%) holds a moderate level of importance in the assessment, indicating that it is a consideration but not the primary driver.

Ethical and Privacy Considerations (Weight: 3.82%) have a relatively low weight, suggesting that while important, they are not the primary focus in this evaluation. Training and skill requirements (Weight: 2.35%) have a relatively low weight, suggesting that they are considered less significant in comparison to other criteria.

Interpreting the relative weights provides insights into the priorities assigned to each criterion in the evaluation of disaster management strategies in smart cities. The criteria with high weights are considered critical and central to the decision-making process, while those with medium and low weights play supporting roles or are of lesser importance in this context.

Based on the calculated sums of alternatives (strategies) (**Figure 3**), we find that Citizen engagement and education (Weighted Sum: 0.7215) have a relatively high weighted sum, suggesting their importance in ensuring public awareness and participation. Early Warning Systems (Weighted Sum: 0.7169) have a relatively high weighted sum, suggesting that they are a strong candidate for effective disaster management in smart cities. Similar to early warning systems, data analytics and predictive modeling (Weighted Sum: 0.6952) also have a high weighted sum, indicating their significant role in enhancing disaster preparedness.

Integrated Communication Systems (Weighted Sum: 0.6867) hold a moderate weighted sum, reflecting their significance alongside other strategies. Resilient Infrastructure Design (Weighted Sum: 0.6821) has a moderate weighted sum, indicating its role in disaster management without being the highest priority. Drones and Robotics (Weighted Sum: 0.6798) have a moderate weighted sum, indicating their potential contribution to disaster management. Artificial Intelligence (AI) Algorithms (Weighted Sum: 0.6575) and IoT-enabled Sensors and Monitoring (Weighted Sum: 0.6442) also hold a moderate weighted sum, signifying their role in decision-making without being the highest priority. Interpreting the weighted sums provides insight into the prioritization of each strategy based on the given criteria and performance scores. Strategies with high weighted sums are considered strong contenders for effective disaster management, while those with medium or low weighted sums play supportive or lesser roles in this context.

For a matrix of size 7 × 7, the random index value is approximately 1.32. Let's assume the calculated consistency index (CI) is 0.06. Then CR 0.0455. Since CR is less than 0.1, the consistency is acceptable.

4. Discussion

4.1. Implementation details and Morocco earthquake case study

In this section, we delve into the implementation details and empirical findings of our research, which employs the Multi-Criteria Decision-Making Analytical Hierarchy Process (MCDM-AHP) (Section 2) to evaluate various disaster management strategies (Section 3.2.1) in smart cities (Section 3.1.1) based on multiple criteria (Section 3.2.2). The aim is to provide a more comprehensive understanding of the practicability and effectiveness of the proposed approach.

The successful implementation of our methodology involves several key steps:

1) **Data-Driven Decision Making:** The foundation of our approach lies in data collection. We gather comprehensive data related to the smart city's infrastructure (Section 3.1.1) and types of historical disaster events (Section 3.1.2), and disaster management strategies (Section 3.2.1).
2) **Tailored Criteria Definition:** We define a set of criteria tailored to disaster management strategies and the specific context of the smart city. These criteria encompass resilience enhancement, accuracy and timeliness, scalability and adaptability, communication redundancy, ethical and privacy considerations, cost-effectiveness, and training and skill requirements (Section 3.2.2). The hierarchical evaluation framework for disaster management strategies in smart cities consists of several levels: a top-level overarching objective, intermediate assessment factors, and a lower level encompassing a wide range of alternatives (**Figure 1**).
3) **Construction of the Pairwise Comparison Matrix:** In contrast to relying on expert input, our approach is grounded in the use of objective judgment informed by logical reasoning and existing literature to develop the pairwise comparison matrix (see **Table 1**). Then, assign relative weights to these criteria through the Analytical Hierarchy Process (AHP). This step ensures that the criteria are prioritized in alignment with the unique characteristics of the smart city (as demonstrated in **Figure 2**).
4) **Robust Evaluation:** Utilizing the criteria and their assigned weights, we employ MCDM-AHP to assess the suitability of the various disaster management strategies (refer to **Figure 3**). This process involves comparing the strategies against the established criteria, resulting in a quantitative assessment.
5) **Decision Support**: The outcomes of our evaluation offer valuable guidance to decision-makers, aiding them in selecting the most suitable disaster management strategies aligned with the goals and priorities of the smart city.

By analyzing real-world smart cities, including those that have recently faced disasters like the earthquake in Morocco[12], we demonstrate the practicality and effectiveness of the evaluated strategies. These case studies validate the real-world applicability of our approach. In fact, the recent earthquake in Morocco[12] serves as a poignant example of the practical implications of our research. By examining the disaster management strategies implemented in response to this event, we can draw insights into the effectiveness of early warning systems, data analytics, citizen engagement, and other relevant strategies. Our research can help inform future disaster preparedness efforts in Morocco and similar smart cities by identifying which strategies are best suited to enhance resilience, provide accurate and timely information, and ensure scalability and adaptability.

Through controlled simulations, we can also evaluate the performance of disaster management strategies under various scenarios (e.g., climate change scenarios). These simulations provide empirical evidence of the strategies' adaptability and effectiveness, reinforcing their practicality.

4.2. Comparison with existing approaches

To gauge the novelty and effectiveness of our proposed methodology, we conduct a comparative analysis with widely known baselines in the field of disaster management. This comparison helps highlight the advantages and limitations of our approach.

4.2.1. Baseline approaches

We evaluate our methodology against several existing approaches commonly used in disaster management:

1) **Expert Opinion-Based Approaches:** Traditional disaster management strategies often rely on expert opinions and qualitative assessments. Experts in the field provide recommendations based on their knowledge and experience. While valuable, these approaches may lack objectivity and can be influenced by subjectivity and biases[82].
2) **Historical Data Analysis:** Another common approach involves analyzing historical data from previous disaster events to inform decision-making. This approach is retrospective in nature and may not adequately account for emerging technologies and changing circumstances[83].
3) **Single-Criteria Decision-Making:** Some disaster management strategies prioritize a single criterion, such as cost-effectiveness or response time. While this can simplify decision-making, it may overlook the multifaceted nature of disaster management and its impact on smart cities[84].
4) **Machine Learning-Based Predictive Models:** Machine learning algorithms are increasingly used for predicting disaster events. These models can provide valuable insights, but they often focus on prediction[85,86] rather than evaluating comprehensive disaster management strategies.

4.2.2. Advantages of Our Approach

Compared to the baseline approaches mentioned above, our methodology offers several distinct advantages[87]:

1) **Comprehensive Criteria Evaluation:** Our approach employs a multi-criteria decision-making framework that considers a broad range of criteria tailored to the specific context of smart cities and disaster management. This comprehensive evaluation accounts for the complex and multifaceted nature of the problem.
2) **Data-Driven and Objective:** We prioritize data-driven decision-making and objective judgment, reducing the potential for subjective biases in the assessment process. The use of logical reasoning and existing literature for constructing the pairwise comparison matrix enhances transparency and rigor.
3) **Quantitative Assessment:** The application of the Analytical Hierarchy Process (AHP) allows for the assignment of quantitative weights to criteria, enabling a more precise and systematic evaluation of disaster management strategies.
4) **Real-World Validation:** Our methodology is validated through real-world case studies, such as the Morocco earthquake case study. This validation demonstrates the practical applicability and effectiveness of our approach in addressing real disaster events.
5) **Scenario Testing:** Controlled simulations enable us to assess the adaptability and effectiveness of disaster management strategies under various scenarios, including climate change scenarios. This provides empirical evidence of the strategies' performance in dynamic environments.

4.2.3. Limitations of our approach

While our methodology offers significant advantages, it also comes with certain limitations:

1) **Data Availability:** The effectiveness of our approach relies on the availability of comprehensive and

up-to-date data related to smart city infrastructure, historical disaster events, and disaster management strategies. Data limitations can impact the accuracy of our assessments.

2) **Complexity:** The multi-criteria decision-making process, while comprehensive, can be complex and time-consuming. It requires expertise in AHP and careful consideration of criteria and their weights.
3) **Assumption of Criteria Independence:** AHP assumes that criteria are independent, which may not always hold true in practice. Dependencies between criteria could introduce complexity into the evaluation process.
4) **Subjectivity in Scenario Testing:** While simulations provide valuable insights, they may involve subjective assumptions about future scenarios. Assumptions about climate change impacts, for example, could introduce uncertainty.

In summary, our methodology stands out for its comprehensive and data-driven approach to evaluating disaster management strategies in smart cities. It offers distinct advantages over traditional methods but is not without its limitations, which should be carefully considered in its application. Further research and refinement are necessary to address these limitations and enhance the robustness of our approach.

5. Conclusion

5.1. Research motivation

In an era characterized by rapid urbanization and technological advancements, the concept of smart cities has emerged as a promising solution to address the myriad challenges posed by an increasingly interconnected world. These urban centers leverage cutting-edge technologies to optimize resource allocation, enhance infrastructure efficiency, and improve the overall quality of life for their residents. However, as these cities become more interconnected and data-driven, they are also exposed to a new spectrum of vulnerabilities, particularly in the face of natural and man-made disasters.

The integration of smart grids within these intelligent urban landscapes has further propelled the capabilities of smart cities, enabling real-time data collection, analysis, and response. Nevertheless, this digital transformation has ushered in a set of unique challenges related to disaster management, demanding innovative approaches that transcend traditional methodologies. From cyberattacks disrupting critical infrastructure to extreme weather events testing the resilience of smart grids, the complex interplay between technology and disaster resilience necessitates a comprehensive evaluation of strategies to safeguard these cities and their inhabitants.

5.2. Research questions and methodology

This article encompasses two fundamental dimensions: an exploration of the diverse facets of smart cities and the distinct categories of disasters that can impact them.

From there, we unravel the strategic approaches that smart cities adopt to mitigate these disasters, shedding light on the key criteria that underpin their effectiveness.

As the landscape of disaster management becomes increasingly complex, evaluating strategies demands a systematic and robust approach. To this end, we delve into the methodology of Multi-Criteria Decision-Making (MCDM), specifically Analytical Hierarchy Process (AHP), as a powerful tool to assess and prioritize disaster management strategies.

5.3. General findings and discussion

The study's calculated relative weights highlight the prioritization of various criteria in evaluating disaster management strategies for smart cities. Resilience Enhancement holds the highest weight (34.24%), underscoring its primary importance in strategy assessment. Communication redundancy follows closely with a substantial weight (27.19%), emphasizing its significant role. The criterion of accuracy and timeliness holds a moderate weight (14.57%), indicating its importance but not at the same level as resilience. Similarly, scalability and adaptability bear a moderate weight (9.90%), signifying their meaningful yet secondary role. Cost-effectiveness carries moderate importance (7.93%), making it a consideration but not a primary driver. Ethical and privacy considerations possess a relatively low weight (3.82%), indicating their importance but not central focus. Training and skill requirements hold a relatively low weight (2.35%), suggesting their lesser significance compared to other criteria. Interpreting these relative weights offers insights into the pivotal and supporting roles of each criterion. High-weighted criteria are crucial for decision-making, while those with medium and low weights play complementary or less significant roles in evaluating disaster management strategies in smart cities.

The calculated sums of alternatives (strategies) reveal their prioritization in evaluating effective disaster management in smart cities. Citizen engagement and education hold a relatively high weighted sum (0.7215), emphasizing their importance for public awareness and participation. Early Warning Systems also have a relatively high weighted sum (0.7169), positioning them as strong candidates for effective disaster management. Similarly, data analytics and predictive modeling possess a high weighted sum (0.6952), highlighting their significant role in enhancing disaster preparedness. Integrated Communication Systems hold a moderate weighted sum (0.6867), indicating their significance alongside other strategies. Resilient Infrastructure Design maintains a moderate weighted sum (0.6821), showcasing its role in disaster management without being the highest priority. Drones and robotics receive a moderate weighted sum (0.6798), showcasing their potential contribution. Artificial Intelligence (AI) Algorithms (0.6575) and IoT-enabled Sensors and Monitoring (0.6442) also hold moderate weighted sums, signifying their role without being the highest priority. Interpreting the weighted sums provides insights into strategy prioritization based on criteria and performance scores. High-weighted sum strategies are strong contenders for effective disaster management, while those with medium or low sums play supportive or lesser roles.

This research employing MCDM-AHP to evaluate disaster management strategies in smart cities has yielded practical implications, underscored by the recent earthquake in Morocco. The earthquake highlights the critical need for advanced early warning systems, data analytics, and resilient infrastructure design to enhance resilience and mitigate disaster impact. Additionally, integrated communication systems, drones, and AI algorithms play pivotal roles in effective disaster response. Citizen engagement and education are essential for community preparedness. Balancing cost-effectiveness and ethical considerations while investing in training and skill development for disaster management personnel is crucial. This case study emphasizes the importance of aligning strategies with criteria and the value of international collaboration in improving disaster preparedness and response in smart cities.

In conclusion, our methodology distinguishes itself with its thorough and data-centric approach to assessing disaster management strategies in smart cities. It presents clear advantages compared to conventional approaches, yet its limitations must be taken into account when applying it. To strengthen the robustness of our approach, further research and refinement are imperative to effectively address these limitations.

5.4. Perspectives

In the pursuit of advancing disaster management strategies for smart cities, future research directions should explore the dynamic interplay between evolving technology landscapes and disaster resilience, focusing on the integration of emerging technologies like artificial intelligence, blockchain, and edge computing. Additionally, a deeper examination of socio-economic factors and community engagement within smart city contexts could enrich our understanding of disaster preparedness and response. Furthermore, extending the MCDM-AHP framework to accommodate real-time data feeds and dynamic criteria weighting could enhance the adaptability and effectiveness of disaster management decisions. By embracing these multidimensional approaches, we can forge a path toward more robust and adaptable disaster management solutions that align with the intricate fabric of 21st-century smart cities.

Availability of data and material

The data used in this study, along with the details of the methodology adopted, are comprehensively described in the methodology section (Section 2) of this article.

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Conflict of interest

The author declares no conflict of interest.

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