SIREN

Safety & Incident Response for building Emergency Networks

D1.1 – State of The Art

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Description	This deliverable document presents a comprehensive State-of-the-Art Analysis focused on the application of Large Language Models (LLMs), Decision Support Optimization, and Next-Generation Communication Networks in disaster response and recovery. It critically evaluates current technologies, identifies capability gaps, and highlights opportunities for innovation across AI-powered disaster planning, real-time decision-making, and resilient communication systems, serving as a foundational reference for the development of the SIREN project's advanced disaster management solutions.

Change Log

Version	Date	Authors	Description of changes
1.0	21.04.2025	Aylin	Initial Draft, Document Structure
1.1	25.04.2025	Aylin	General Overview of AI in Crisis Management Overview of Large Language Models (LLMs)
1.2	05.05.2025	Aylin	Key Milestones in NLP: From BERT to GPT Fine-tuning and Adaptability of LLMs Challenges in Applying LLMs in Disaster Scenarios
1.3	21.05.2025	Andrey, Ali, Pouria	SoA analysis of 3GPP standards related to technologies and solutions for emergency and disaster-resilient communication networks
1.4	30.05.2025	Haluk	Selection of academic and industry resources focusing on Self-Organizing Networks (SON) and their application in optimizing mobile networks during and after disasters
1.5	10.06.2025	Andrey, Ali, Pouria	Analyses of new 6G use cases relevant to disaster scenarios and 6G use cases about AMRs that can be involved in disaster scenarios. Proposed new use case on multi-MNO cooperative service continuity in case of disasters and agentic AI-based communications as a tool to address challenges in traditional networks for disaster scenarios
1.6	15.06.2025	PT Consortium	Wearable Tech for Emergency Responders SoTA Review added
1.7	30.06.2025	UK Consortium	Advanced Decision Support systems for Disaster Management added

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Document Glossary

Acronym	Definition
Agentic AI	A form of AI capable of autonomous action and decision-making in dynamic environments. Used in SIREN to enable self-reconfiguring communication networks and adaptive coordination.
BERT	(Bidirectional Encoder Representations from Transformers): A type of transformer-based LLM that understands language context in both directions. Used in SIREN for information extraction and decision-support modelling.
CNN	(Convolutional Neural Network) A deep learning algorithm especially effective in image recognition and spatial data analysis. Integrated into SIREN for urban change detection and situational mapping.
Disaster GPT	A domain-specific application of Generative Pre-trained Transformers (GPT) for disaster logistics and planning. Evaluated in the SIREN project for effectiveness in operational settings.
GIS	(Geographic Information Systems): Systems for capturing, storing, analyzing, and visualizing spatial data. Used in SIREN for coordinated humanitarian logistics and urban situational awareness.
Human-in-the-Loop (HITL)	A system design where humans oversee and guide AI decisions, particularly in high-stakes environments like disaster response. Promoted in SIREN for ethical and accountable AI use.
LLM	Large Language Models: AI models trained on vast text corpora to perform language tasks like summarization, translation, and reasoning. In SIREN, LLMs support scenario planning, information synthesis, and decision support.
LSTM	(Long Short-Term Memory): A type of recurrent neural network effective for time-series data and sequences. Used in SIREN for predictive modeling and temporal data analysis.
Mesh Network	A communication network where each node relays data for the network. Enhances connectivity in the field. Used in SIREN's wearable systems for resilient responder communication.
PPE	(Personal Protective Equipment): Clothing or equipment worn to minimize health risks. In SIREN, PPE is enhanced with embedded physiological monitoring sensors.
GPT	Generative Pre-trained Transformers: A type of LLM developed by OpenAI, capable of generating coherent and contextually appropriate natural language text. Used for summarizing data, generating alerts, and automating reports in crisis scenarios.
NLP	Natural Language Processing: A branch of AI that enables machines to interpret, understand, and respond to human language. In crisis response, NLP transforms unstructured data (e.g., social media posts) into structured formats suitable for analysis.
Unstructured Textual Data	Information not organized in a pre-defined format (e.g., tweets, emergency notes). AI systems convert this into semantically valid formats to extract meaning and support operational decisions.
Semantically Valid Formats	Data that has been structured and enriched with contextual meaning, making it interpretable by machines and actionable for decision-makers.
GPT-4	A state-of-the-art generative language model from OpenAI. In disaster management, it powers tools like DisasterResponseGPT and emergency chatbots that interpret data, generate action plans, and simplify communication.
LangChain	A framework for building applications with LLMs. In disaster response, it has been used with GPT-4 to build bots that can access structured information like FEMA guidelines.
NER	Named Entity Recognition: A technique in NLP for identifying and classifying entities (like names, locations, organizations) in text. Combined with DistilBERT, it has been used to extract geographic information during disasters such as floods.
AL	Active Learning - A training strategy where the model selects the most informative examples for labeling. Applied in disaster tweet classification to reduce the effort needed for annotating large datasets.
LoRA	Low-Rank Adaptation: A parameter-efficient fine-tuning technique that inserts trainable low-rank matrices into models to reduce computational demands during LLM fine-tuning.
ReFT	Representation Fine-Tuning: A technique that updates only a small part of an LLM's internal representations, enabling task-specific behavior without full model retraining.
LVLMs	Large Vision Language Models: AI models combining vision and language understanding. Used in disaster tools like DisasTeller to automate on-site assessment, alert generation, and planning based on both image and text inputs.

Acronym	Definition
Geo-AI	(Geospatial Artificial Intelligence): An interdisciplinary field combining geographic information science with artificial intelligence (especially machine learning and deep learning) to analyze, predict, and visualize spatial phenomena in real time.
Mapillary	A service for collecting, sharing, and using street-level imagery from user contributions.
Spatial OLAP	Online Analytical Processing: Tools and techniques for performing complex queries on multidimensional spatial data, enabling fast spatial data analysis and decision-making in emergency response.
NLU	Natural Language Understanding: A component of AI systems that interprets human language queries (e.g., "Where are accessible shelters?") and maps them to structured data for retrieval or analysis.
BPMN	Business Process Model and Notation: A graphical standard for modeling business workflows. In the Dedoctive context, it's used to define structured, agent-based workflows that wrap LLM responses.
CityGML / CityJSON	Open standards for encoding and exchanging semantic 3D city models, allowing consistent representation of urban features with detailed attributes relevant to emergency scenarios.
UIDs	Unique Identifiers: Persistent, unique codes assigned to spatial features, assets, or infrastructure elements that enable consistent semantic and spatial linking across diverse datasets, facilitating coordinated disaster response and real-time situational awareness.
SDI	Spatial Data Infrastructure: A framework of policies, standards, technologies, and people designed to facilitate sharing and management of geospatial data among multiple agencies for enhanced disaster response coordination.
ITS	Intelligent Transportation Systems: Technologies combining communications, sensors, and control systems to monitor, manage, and optimize traffic flow, mobility, and safety in real time, especially under emergency conditions.
VGI	Volunteered Geographic Information: User-generated spatial data contributed by citizens during emergencies to supplement authoritative datasets, enhancing situational awareness and responsiveness.
UAV	Unmanned Aerial Vehicles: Remotely piloted or autonomous aerial platforms used for rapid, high-resolution data collection (imagery, LiDAR) in disaster zones to support mapping, damage assessment, and situational awareness.
BIM	Building Information Modeling: Digital representations of physical and functional characteristics of infrastructure, which can be integrated with UAV data for detailed structural assessments and reconstruction planning post-disaster.
MVS	Multi-View Stereo: A computer vision technique that converts 2D aerial imagery into semantically segmented 3D models, aiding in the identification of disaster damage and logistics base locations.
MLS	Technology for capturing precise elevation and structural data; integration challenges exist in combining data streams for unified high-resolution terrain and infrastructure models.
3GPP	3rd Generation Partnership Project
ATSSS	Access Traffic Steering, Switching, and Splitting): A multi-access feature allowing simultaneous use of 5G and Wi-Fi to ensure redundancy, load balancing, and robustness in disaster scenarios.
TN/NTN Integration	Integration of Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN), like LEO satellites, to ensure connectivity where ground networks are unavailable or damaged.
MCPTT	Mission-Critical Push-to-Talk: Group voice communication over LTE/5G, designed for public safety and emergency teams with high reliability and priority handling.
C-V2X	Cellular Vehicle-to-Everything: A communication system enabling direct exchange of information between vehicles and infrastructure, useful for mobility and rescue coordination.
D2D	Communication method that enables devices to connect directly without base stations, critical in infrastructure-damaged zones.
PWS	Public Warning System: Framework for sending emergency alerts to mobile users using cell broadcast and ETWS, especially during large-scale disasters.
CBS	Cell Broadcast Service: Technology that delivers time-critical, location-specific alerts to multiple users without network congestion.
ETWS	Earthquake and Tsunami Warning System: Specialized alert system under 3GPP to notify populations in real time about seismic and tsunami events.
LEO Satellites	Low Earth Orbit: Satellites orbiting between 500–2000 km above Earth used in NTN systems to provide communication coverage in remote/disaster areas.
QoS	Quality of Service: Set of network performance parameters (latency, reliability, bandwidth) used to prioritize critical communications.

Acronym	Definition
GNSS	Global Navigation Satellite System: Satellite-based navigation systems like GPS. 6G aims to maintain services even during GNSS outages, especially in emergencies.
UAV Swarms	Groups of UAVs coordinating their actions, often via AI agents, for tasks like area mapping, search-and-rescue, or ad hoc network coverage.
AMRs	Robots that can navigate and operate in unstructured environments, useful for search, delivery, or inspection in disaster scenarios.
SAR	Search And Rescue: Emergency operations involving locating and assisting people in disaster-struck areas. AI-enabled multi-agent systems enhance coordination across UAVs, robots, and humans.
Mission-Aware Networks	Networks that prioritize data and adapt behavior according to the urgency, goals, and context of the operation (e.g., prioritizing survivor detection data).
Multi-Agent Collaboration	Coordination among diverse autonomous agents (UAVs, AMRs, sensors) to share goals, learn jointly, and dynamically plan operations.
Decentralized Task Allocation	Distribution of work among AI agents based on current capabilities, location, and mission state—enabling resilient collaboration with minimal central control.
MNO	Mobile Network Operator: A telecommunications provider that offers mobile communication services to subscribers.
MNO-A / MNO-B	Designations for mobile operators in the use case: MNO-A is the one with a disrupted network; MNO-B is the assisting operator providing fallback connectivity.
PLMN	Public Land Mobile Network: A wireless communications network established and operated by an MNO, which includes radio access and core network infrastructure.
IETF ALTO	Application-Layer Traffic Optimization: A protocol to provide applications with network information to optimize inter-domain decisions.
NG911 / NG112	Next Generation 911/112: Enhanced emergency calling systems offering multimedia, geolocation, and improved network routing for public safety.
AML	Advanced Mobile Location: A feature that automatically sends a smartphone's precise location to emergency services when calling 112/911.
CDRs	Call Detail Records: Anonymized records of mobile calls and messages used to track movement patterns post-disaster.
FME	Flexible Management Entity: A proposed mechanism to improve LTE network flexibility and resilience under partial outages.
SON	Self-Organizing Networks: Networks with autonomous capabilities for configuration, optimization, and healing, especially useful in dynamic or disaster-prone environments
PPE	Personal Protective Equipment: Equipment worn to minimize exposure to hazards that cause serious injuries and illnesses, such as fire-resistant clothing or sensor-integrated boots.
Hexoskin Smart Shirt	A commercial wearable that measures cardiac, respiratory, and activity metrics to monitor physical and mental health.
ARMOR Wearable	A heat stress monitoring wearable by EVALAN IoT that provides real-time biometric data.
IMUs	Inertial Measurement Units: Sensors measuring movement and orientation, often used in wearable technology for motion analysis.
HSF	Hierarchically Sandwiched Fabric (HSF) Sensors: Advanced textile sensors that detect temperature and pressure simultaneously under extreme heat (up to 400 °C), used in firefighting gear for fire warnings and motion sensing.
EDA	Electrodermal Activity: A physiological measure of skin conductance changes, indicating stress or emotional arousal.
HRIS	Human Resource Information Systems: Systems that store and manage data on personnel skills, training, certifications, and performance records to support resource allocation.
DSS	Decision Support Systems: Technology-based systems designed to support planning, coordination, and decision-making during disaster scenarios using data analytics, optimization, and AI.
MOO	Multi-objective Optimization: A mathematical approach that enables decision-makers to evaluate and balance multiple conflicting goals (e.g., minimizing response time vs. maximizing resource use) to find optimal or compromise solutions.
Agent-Based Modelling	A simulation approach where individual agents (e.g., responders, vehicles) follow rules and interact to model complex systems such as disaster responses.
Scenario-Based Optimization	Planning method that considers different possible future scenarios to guide robust decision-making in uncertain environments.
Spatial Asset Tracking	Monitoring the real-time locations of vehicles, equipment, and personnel using technologies like RFID, GPS, and IoT for effective coordination.
Critical Path Mapping	Identifying the most important sequence of actions or routes to deliver aid or restore services efficiently in constrained environments.

Executive Summary

Purpose of The Document

The primary objective of this document is to conduct a **comprehensive State-of-the-Art (SoTA) Analysis** focused on enhancing **disaster response systems**, particularly in the **Safety & Incident Response** sector. The document synthesizes the latest advancements, technologies, and methodologies used in managing emergency networks and interventions. Specifically, it aims to provide a thorough understanding of key technologies that play a crucial role in improving disaster response and recovery efforts. These include:

Large Language Models (LLMs): The document explores how LLMs, such as Generative Pre-trained Transformers (GPT), can revolutionize disaster management by automating and expediting tasks such as generating response plans, managing communication, and providing real-time support to decision-makers. By integrating LLMs, emergency networks can become more responsive, data-driven, and adaptive, optimizing processes such as incident reporting, resource allocation, and scenario analysis.

Decision Support Optimization: The analysis investigates the use of decision-support tools that enhance the coordination of resources, workforce, and assets during emergency response operations. By employing AI-driven optimization techniques, these tools can integrate various data streams—such as real-time environmental data, communication reports, and ground conditions—to optimize resource deployment and task prioritization. The document highlights existing models and identifies opportunities to improve these systems to better handle complex, multi-objective decision-making, particularly in uncertain, rapidly changing disaster environments.

Communication Networks: The document examines current and evolving 3GPP standards critical for disaster-resilient communication. Despite the current advancements, existing solutions face challenges like rigidity, insufficient real-time autonomy, fragmented interoperability, and limited use of AI, restricting their adaptability and effectiveness during dynamic disaster situations. To address these gaps, the document advocates for integrating agentic AI into network architectures, enabling autonomous network reconfiguration, real-time decision-making, enhanced situational awareness, and seamless coordination between terrestrial and non-terrestrial systems. This AI-driven approach promises significant improvements in resilience, flexibility, and collaboration, ensuring robust emergency communications in complex and rapidly evolving disaster environments.

Physiological Monitoring: Emergency responders often face physical and mental health risks in disaster environments, making physiological monitoring a crucial component of incident response. The document discusses the latest wearables and sensor technologies, integrated into Personal Protective Equipment (PPE) and other devices, that enable the continuous monitoring of health parameters such as heart rate, fatigue levels, body temperature, and stress. These devices enhance the safety of responders by providing real-time feedback and ensuring prompt medical intervention when necessary.

Through the SoTA analysis, the SIREN consortium aims to:

1-Identify Strengths and Limitations: It highlights where current technologies excel in supporting disaster response efforts and identifies gaps or limitations in these technologies. By recognizing these areas, the document sets the foundation for improving and refining these systems.

2-Pinpoint Opportunities for Improvement: By synthesizing insights across multiple domains (AI, communication, physiological monitoring), the document uncovers areas where advancements can be made, leading to more effective disaster response mechanisms.

3-Provide Insights for Advanced Disaster Management Systems: This document serves as a roadmap for stakeholders, including disaster management agencies, policymakers, and technology developers, to develop more sophisticated, integrated, and adaptive disaster management solutions. The analysis will help these stakeholders make informed decisions about which technologies and methodologies to adopt in building more resilient and responsive emergency networks.

Ultimately, the purpose of the publicly available SIREN State of The Art document is to foster a deeper understanding of how emerging technologies, particularly AI-driven systems and advanced communication networks, can be integrated into disaster response strategies. By leveraging these tools effectively, Safety & Incident Response systems can become more efficient, adaptable, and capable of providing immediate, real-time solutions during emergency situations.

Overview of The SIREN Project

The SIREN Project (Smart Integrated Resilience and Emergency Network) seeks to enhance disaster response capabilities by integrating AI, machine learning, and advanced decision-support systems. The project aims to improve coordination, resource allocation, workforce management, communication, and situational awareness during disasters. By examining the latest technologies and methodologies, SIREN strives to develop optimized, AI-driven solutions to improve disaster management effectiveness and reduce the economic and social impacts of natural disasters. **SIREN project aims, in a multi-national collaboration, to expand capabilities of humanitarian aid portals to deliver GIS Integrated & Coordinated Humanitarian Aid Logistics Platform.**

Introduction

Background and Motivation

In recent years, Europe and its surrounding regions have experienced a series of catastrophic natural and man-made disasters, underscoring the urgent need for a robust, coordinated, and technologically advanced disaster response capability. Events such as the 2020 Beirut explosion, the 2021 floods in Central Europe, the widespread wildfires in Sweden in 2018, the recurring winter floods in the UK, and the devastating earthquakes in Türkiye in 2023, have collectively led to the loss of tens of thousands of lives, displacement of millions, and economic losses amounting to billions of euros.

These disasters have revealed systemic vulnerabilities in current emergency response systems. While first responders, humanitarian organizations, and civil protection agencies act swiftly and courageously, their efforts are often hampered by fragmented communication, damaged infrastructure, inefficient logistics, and a lack of coordinated decision-making frameworks. Post-disaster conditions—marked by debris-filled roads, disrupted power and communications infrastructure, and overwhelmed health systems—demand more than traditional emergency management approaches. They call for a paradigm shift powered by technology, real-time data, and interoperable systems.

Against this backdrop, **the motivation for delivering a comprehensive State-of-the-Art (SoTA) analysis** arises from the need to:

1. **Understand the Current Technological Landscape**: A wide range of technologies, including AI, decision-support systems, communication networks (both terrestrial and satellite), real-time simulation, and physiological monitoring tools, are being developed and deployed in isolation. Yet, their integration and adaptability to dynamic disaster scenarios remain limited. The SoTA

analysis will survey these technologies, assess their current maturity, and examine how they can be harnessed synergistically to transform disaster response.

2. **Address Critical Gaps and Bottlenecks**: Existing systems struggle with sorting and managing aid donations, optimizing transportation and routing under uncertainty, and ensuring real-time collaboration between diverse actors. The analysis aims to pinpoint these gaps—such as poor data quality, latency in decision-making, and lack of communication redundancy—and identify innovative approaches to overcome them.
3. **Enable Evidence-Based Decision Making**: The chaos and complexity of disaster zones require human-in-the-loop AI systems that offer explainable, justifiable recommendations under conditions of uncertainty. Decision-makers must be supported with tools that fuse simulation, optimization, and situational awareness—updated in real time—to balance competing priorities and resource constraints.
4. **Strengthen Communication Resilience**: Failures in network infrastructure during disasters often lead to delays in rescue and relief operations. The analysis will explore the state of communication systems and evaluate how scalable, AI-based architectures can support uninterrupted coordination across agencies and responders.
5. **Ensure Interoperability and Coordination**: Disaster response is inherently multi-agency and cross-border. Current tools and protocols often lack interoperability, leading to duplication of effort, gaps in service delivery, and data silos. A key aim of the analysis is to highlight existing standards, protocols, and tools that promote collaboration and offer actionable pathways to enhance cooperation across national and organizational boundaries.
6. **Integrate Simulation for Dynamic Scenario Planning**: Simulation technologies can enable digital twins of disaster-affected regions to visualize evolving conditions, test intervention strategies, and anticipate cascading failures (e.g., power outages leading to sewage issues or medical shortages). This analysis will review simulation capabilities and their readiness for operational deployment in real-time scenarios.
7. **Meet User-Centric and Humanitarian Needs**: The ultimate beneficiaries of enhanced disaster response systems affect populations. Timely access to food, water, shelter, medical care, and communication can be the difference between life and death. The SoTA analysis will reflect the perspective of key stakeholders—disaster victims, humanitarian organizations, first responders, and national authorities—and ensure that technological interventions are guided by human-centered design and ethical considerations.
8. **Support Strategic Planning for Future Preparedness**: As climate change continues to amplify the frequency and severity of natural disasters, and geopolitical risks introduce further complexity, there is a growing need for predictive, adaptive, and scalable systems. The SoTA analysis will not only assess current capabilities but also provide foresight into emerging trends and strategic directions for research and development in the disaster response domain.

Technological Context

The technological context of the SIREN Project is first centered on evaluating and advancing the application of **Artificial Intelligence (AI)**, particularly machine learning (ML) and large language models (LLMs), within disaster response systems. It addresses current gaps in needs assessment and logistics coordination by benchmarking state-of-the-art techniques, leveraging validated open-source and social media data, and applying multimodal data fusion and sentiment analysis to enhance situational understanding. Rather than building new data infrastructures, the task focuses on optimizing existing approaches and technologies to improve the speed and accuracy of response efforts. Additionally, the task critically examines the role of LLMs, such as Disaster GPT, in supporting disaster logistics through comprehensive evaluation, simulation-based demonstrations, and the development of a strategic research roadmap. This will lay the groundwork for the responsible and effective integration of LLMs into future operational systems, enabling smarter, more agile disaster response capabilities.

At the **decision support layer**, SIREN introduces several innovations that surpass current models. Its AI-powered Decision Support System enables real-time coordination, dynamically adapting task prioritization, resource allocation, and team deployment based on incoming data. Workforce and equipment management is enhanced through machine learning and real-time analytics, optimizing scheduling, routing, and coordination—even in disconnected areas—using graph-based methods. Needs and resource mapping leverages expert-validated models and real-time data classification to deliver accurate insights, even from fragmented sources. In debris management, SIREN supports coordinated multi-team efforts, sustainability-focused prioritization, and dynamic mapping that adapts to changing conditions. For wildfire response, SIREN integrates intelligent suppression algorithms into partner tools, enhancing decision-making and coordination with semi-automated strategies informed by live data.

In the domain of responder support, SIREN offers a unique wearable-based system for **physiological and skills monitoring**. These multiparameter wearables not only collect vitals in real time, but they can also process and reduce data locally, minimizing bandwidth use—crucial in environments with compromised networks. With peer-to-peer, self-healing communication capabilities, the sensors can continue to operate in mesh configurations, ensuring data is shared and interpreted even in isolated conditions. This enhances back-office decision-making and allows better, safer responder deployment based on real physiological readiness.

Finally, SIREN advances emergency **communications** beyond current 3GPP standards, addressing their existing limitations. Today's emergency networks are often static, rigid, and insufficiently adaptive to real-time disaster scenarios. SIREN introduces an innovative, resilient, and intelligent communication architecture driven by agentic. This next-generation framework provides autonomous network reconfiguration through AI-driven decision-making, ensuring adaptability and responsiveness.

Through these integrated technological innovations, the SIREN project moves decisively beyond the current state-of-the-art, offering a truly adaptive, intelligent, and human-aware disaster response system that can function under the most challenging conditions.

Research and Innovation Objectives

The primary research and innovation objective of the SIREN project is to develop an integrated, AI-powered, real-time disaster response and decision support ecosystem that surpasses current state-of-the-art (SoTA) capabilities. SIREN aims to deliver a scalable, modular, and intelligent platform capable of optimizing humanitarian aid and emergency coordination in rapidly evolving disaster environments through advanced machine learning, semantic analysis, and resilient communication systems.

This objective is supported by **key innovation pillars**:

- **AI-Driven Decision Support Optimization**: Leveraging bidirectional transformer-based LLMs (notably BERT and enriched architectures such as CNN, LSTM, and bi-LSTM), SIREN advances context-aware action planning and information synthesis in disaster response. Novel AI integration leveraging the agentic Dedoctive platform from Collaboration Tools Ltd supports real-time case coordination, resource optimization, and role-specific response generation.
- **Semantic 3D Spatial Profiling and Urban Change Detection**: Innovations from Urban Hawk enable dynamic semantic mapping and structural profiling using fused spatial data and 3D models. This supports detailed situational awareness, structural damage assessment, and informed propagation models for mobility, logistics, and debris clearance planning.

- **Real-Time Predictive Simulation and Scenario Modelling**: By integrating multi-source partner data into Polaron's simulation engine, the project enables real-time "what-if" scenario planning. This includes social and cultural weighting in AI-driven decision logic, providing user-validated and context-aware recommendations.
- **Wearable-Enabled Human Monitoring and Skill Mapping**: SIREN introduces a new generation of edge-computing-enabled physiological and skill-monitoring wearables. These provide local data processing and self-healing communication, allowing continuous insight into responder well-being and performance despite degraded infrastructure.
- **Agentic Emergency Communication Networks:** The project innovates beyond existing 3GPP standards by developing an intelligent, autonomous, and adaptable emergency communication architecture powered by agentic AI. This next-generation framework enables dynamic network reconfiguration, real-time responsiveness, and context-aware connectivity, ensuring robust and uninterrupted emergency communication under rapidly evolving disaster conditions.
- **Enhanced Debris Management and Logistics Intelligence**: SIREN proposes a multi-layered debris management strategy involving advanced AI models for clearance prioritization, sustainability scoring, and multi-task team coordination. This approach integrates real-time spatial tracking and resource verification for optimized field operations.

Together, these innovations address key limitations of current disaster response systems, including lack of adaptability, fragmented data integration, communication breakdowns, and inefficient resource allocation. SIREN's scientific and technological breakthroughs align with SMART goals by enabling faster, more effective, and human-centric emergency responses, ultimately saving lives, reducing costs, and enhancing long-term resilience in disaster-stricken communities.

Methodology for SoTA Review and Gap Analysis

The objective is to systematically map the current landscape of research, technologies, and innovations relevant to the SIREN project—focused on optimizing disaster response interventions. The methodology follows a structured approach combining evidence synthesis, comparative evaluation, and gap identification across key domains where innovation is required to improve disaster preparedness and response capabilities.

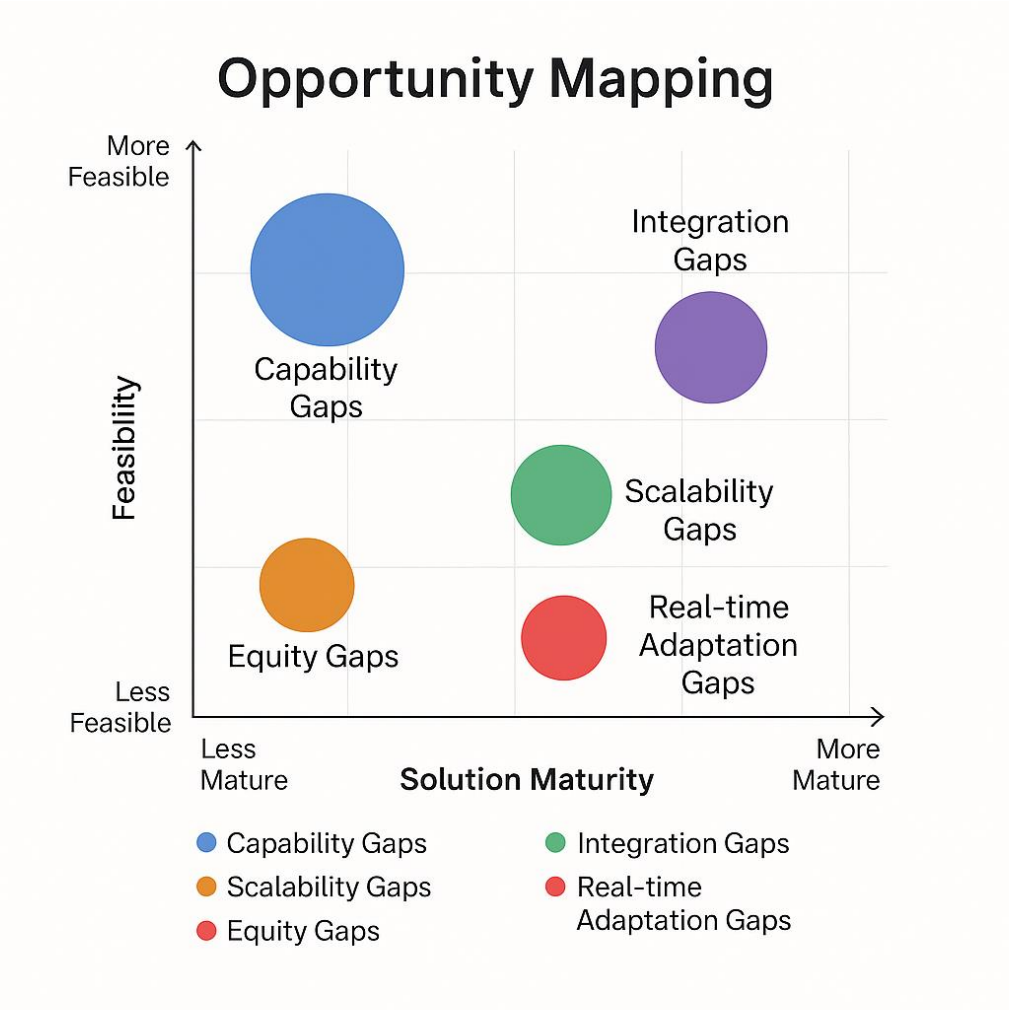
A multi-pronged approach is going to be used to identify relevant works:

- **Academic Literature**: A comprehensive review of recent publications (2015–2024) from top-ranked journals and conferences (e.g., OR, AI, HCI, telecommunications, emergency management, public health) was conducted using databases such as Scopus, Web of Science, IEEE Xplore, and Google Scholar.
- **Industry Reports and Standards**: Reports from organizations such as 3GPP, WHO, FEMA, and EENA were reviewed to understand evolving standards, technology readiness levels (TRL), and deployment strategies.
- **Experimental and Applied Studies**: Special focus was placed on works demonstrating field experiments, real-world case studies, or simulation-based validation, particularly those leveraging AI or optimization in disaster scenarios.
- **Emerging Tools and Platforms**: Tools such as GPT-3.5/4, Bard, and AI-enabled decision support systems were critically evaluated for capabilities, limitations, and potential deployment in emergency settings.

Identified works are analyzed through the lens of current operational limitations and future needs. Gaps are categorized as:

- **Capability Gaps** – Missing or underdeveloped technical functionalities (e.g., coordination under cascading disasters).
- **Integration Gaps** – Disconnected systems and lack of interoperability between technologies and organizational workflows.
- **Scalability Gaps** – Solutions that work in isolated experiments but lack robustness in large-scale, real-world applications.
- **Equity Gaps** – Failure to account for fairness, inclusivity, or differential impacts on affected populations.
- **Real-time Adaptation Gaps** – Static models or delayed decision-making pipelines in time-sensitive environments.

A visual mapping of gaps against solution maturity and feasibility is used to illustrate prioritize future development directions within the SIREN ecosystem:



Use of LLM for Disaster Response

General Overview of AI in Crisis Management

Artificial Intelligence (AI) has emerged as a transformative tool in crisis management, revolutionizing how information is gathered, processed, validated, and utilized in real-time during emergencies. The integration of AI technologies, such as Large Language Models (LLMs), Generative Pre-trained Transformers (GPT), Natural Language Processing (NLP), and advanced social media rendering, has significantly enhanced decision-making, response coordination, and resource deployment in crises. This section provides an overview of AI's capabilities and applications in crisis management, focusing on how AI-driven systems can improve the speed, accuracy, and efficiency of operations.

Large Language Models (LLMs) and Generative Pre-trained Transformers (GPT)

LLMs like GPT are at the forefront of AI's application in crisis management. These models can understand, generate, and interact with human language, allowing them to process and analyze vast amounts of textual information generated during a crisis[1]. The ability of LLMs to generate coherent, contextually appropriate responses makes them invaluable tools for quickly disseminating crucial information to first responders, field operators, and decision-makers.

In crisis situations, GPT models[2] can be used to automatically generate reports, summarize key findings, and provide actionable insights in real-time. They can also assist in drafting communications, alerts, and updates, significantly reducing the manual workload for responders and authorities.

Natural Language Processing (NLP)

NLP is essential for converting unstructured textual data—such as social media posts, news articles, emergency reports, and field notes—into a structured, semantically valid format. In crisis management, vast amounts of unstructured data are generated from multiple sources, including social media platforms, field operations, sensors, and citizen reports. NLP algorithms can identify key information, extract relevant details, and categorize data, transforming it into a usable format for further analysis[3].

For example, NLP can be used to detect patterns or emerging threats from social media conversations, providing early warnings of crises such as natural disasters, civil unrest, or disease outbreaks. This transformation of raw data into structured formats allows responders to more effectively assess the situation and make informed decisions[4].

Social Media Rendering

Social media is a crucial source of real-time information during a crisis. AI systems equipped with social media rendering capabilities can analyze and interpret posts, tweets, videos, and images shared by the public. AI-driven sentiment analysis can gauge public sentiment, identify urgent issues, and track the spread of misinformation, helping responders prioritize their actions. Moreover,

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[1] Cantini, R., Cosentino, C., Marozzo, F., Talia, D., & Trunfio, P. (2025). Harnessing prompt-based large language models for disaster monitoring and automated reporting from social media feedback. *Online Social Networks and Media, 45*, 100295. https://doi.org/10.1016/j.osnem.2024.100295

[2] Sufi, F. K. (2024). A systematic review on the dimensions of open-source disaster intelligence using GPT. *Journal of Economy and Technology, 2*, 62-78. https://doi.org/10.1016/j.ject.2024.03.004

[3] Acikara, T., Xia, B., Yigitcanlar, T., & Hon, C. (2023). Contribution of Social Media Analytics to Disaster Response Effectiveness: A Systematic Review of the Literature. *Sustainability*, *15*(11), 8860. https://doi.org/10.3390/su15118860

[4] Ponce-López, V., Spataru, C. Social media data analysis framework for disaster response. *Discov Artif Intell* **2**, 10 (2022). https://doi.org/10.1007/s44163-022-00026-4

by aggregating and categorizing posts from multiple platforms, AI tools can present responders with a clearer picture of the situation on the ground, such as locating disaster hotspots or areas requiring immediate attention[5].

Converting Unstructured Textual Data into Semantically Valid Formats

In many crisis scenarios, the data generated is unstructured and lacks the necessary context for immediate action. AI-powered systems, especially those using NLP and machine learning algorithms, can convert this unstructured data into semantically valid formats. This enables systems to understand the meaning behind the data, classify it, and determine its relevance to specific operational objectives.

For instance, a field report that is vague or written informally may be processed by AI to extract essential information such as locations, damage assessments, and safety concerns. This process is vital for transforming chaotic, informal inputs into a format that is compatible with crisis management systems, facilitating more effective response coordination[6].

Semi-Automatic Validation of Data

In crisis situations, the accuracy and reliability of data are paramount. AI systems can facilitate the semi-automatic validation of data by cross-referencing information across multiple sources, checking for consistency, and flagging discrepancies. While human oversight remains essential, AI can significantly reduce the time and effort required to validate large volumes of incoming data, ensuring that responders have access to the most reliable information.

For example, AI could automatically validate incoming reports of damage or casualties by comparing them with satellite imagery or data from other sensors, highlighting inconsistencies that require further investigation. This validation process ensures that decision-makers are not overwhelmed by false or misleading data, which could delay critical actions[7].

Feeding Information into Systems for Decision-Makers

AI systems can be used to funnel structured, validated data[8] into decision-support systems, providing crisis managers with a clear overview of the situation. These systems can present visual dashboards, maps, and real-time data feeds that highlight key metrics such as the severity of the crisis, resource availability, and areas of high risk.

By integrating AI into decision-making systems, decision-makers can quickly assess the status, predict possible outcomes, and allocate resources more effectively. For example, AI models can forecast the likely trajectory of wildfire based on current conditions and provide recommendations for evacuation or resource deployment[9].

Allowing Responders to Query Structured, Validated Data Using Informal Natural Language

A critical advantage of AI in crisis management is its ability to allow responders to query validated data using natural, informal language. Traditionally, querying structured data requires specialized

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[5] Ilyas, B., & Sharifi, A. (2025). A systematic review of social media-based sentiment analysis in disaster risk management. *International Journal of Disaster Risk Reduction*, 105487. https://doi.org/10.1016/j.ijdrr.2025.105487

[6] Tounsi A, Temimi M. A systematic review of natural language processing applications for hydrometeorological hazards assessment. Nat Hazards (Dordr). 2023;116(3):2819-2870. https://10.1007/s11069-023-05842-0

[7] Rolla, J., Khuller, A., An, K., Emberson, R., Fielding, E., Schultz, L., & Miner, K. (2025). Satellite-aided disaster response. *AGU Advances*. https://doi.org/10.1029/2024AV001395

[8] Chandra, Ritesh & Kumar, Shashi & Patra, Rushil & Agarwal, Sonali. (2024). Decision support system for Forest fire management using Ontology with Big Data and LLMs. 10.48550/arXiv.2405.11346.

[9] Bhowmik, R. T., Jung, Y. S., Aguilera, J. A., Prunicki, M. M., & Nadeau, K. (2023). A multi-modal wildfire prediction and early-warning system based on a novel machine learning framework. *Journal of Environmental Management, 341*, 117908. https://doi.org/10.1016/j.jenvman.2023.117908

knowledge and expertise. However, AI systems equipped with NLP capabilities enable responders to pose questions in simple, conversational language. For instance, a responder might ask, “What are the latest updates on the flooding in the northern region?” and receive a concise, relevant answer derived from validated data sources[10].

This capability significantly improves the accessibility and usability of crisis management systems, particularly for responders who may not have specialized training in data analytics. It also ensures that information can be quickly retrieved and acted upon in high-pressure situations.

Quick Processing of Natural Language Queries from Field Operations

AI can process natural language queries from field operations in real time, providing context-aware responses that help responders make informed decisions[11]. Field operators can submit queries related to the crisis—such as requesting information about road closures, shelter locations, or the availability of medical supplies—and receive accurate, actionable answers almost immediately.

This quick processing capability is vital in fast-moving crisis scenarios, where every second counts. AI systems can also be designed to provide real-time updates based on changing conditions, ensuring that responders always have the most up-to-date information at their fingertips.

Overview of Large Language Models (LLMs)

Large Language Models (LLMs), including architectures such as OpenAI's GPT (Generative Pre-trained Transformer), represent a significant advancement in artificial intelligence, particularly in the domain of natural language understanding and generation. Their ability to process, contextualize, and generate human-like language at scale positions them as critical enablers in the digital transformation of disaster and crisis management[12].
LLMs are trained on extensive corpora comprising diverse linguistic patterns, enabling them to generalize across a wide range of domains and perform tasks with minimal task-specific tuning[13]. This makes them exceptionally well-suited to environments where data is heterogeneous, rapidly evolving, and often unstructured—as is the case during emergencies and disasters.

In the context of disaster management, LLMs offer a unique set of capabilities:

- **Real-time Information Synthesis:** LLMs can ingest and summarize vast volumes of unstructured textual data such as emergency reports, social media feeds, citizen-generated content, and news articles. This capacity allows emergency operations centers to maintain a real-time, high-level understanding of unfolding events without the manual overhead traditionally required for data triage and review[14].
- **Automated Report Generation:** LLMs can generate structured reports from chaotic and informal data streams. These outputs can include incident summaries, risk assessments, damage estimations, and response recommendations. Importantly, these reports can be

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[10] Rolla, J., Khuller, A., An, K., Emberson, R., Fielding, E., Schultz, L., & Miner, K. (2025). Satellite-aided disaster response. *AGU Advances*. https://doi.org/10.1029/2024AV001395

[11] Rolla, J., Khuller, A., An, K., Emberson, R., Fielding, E., Schultz, L., & Miner, K. (2025). Satellite-aided disaster response. *AGU Advances*. https://doi.org/10.1029/2024AV001395

[12] Sufi, F. K. (2024). A systematic review on the dimensions of open-source disaster intelligence using GPT. *Journal of Economy and Technology, 2*, 62–78. https://doi.org/10.1016/j.ject.2024.03.004

[13] Cantini, R., Cosentino, C., Marozzo, F., Talia, D., & Trunfio, P. (2025). Harnessing prompt-based large language models for disaster monitoring and automated reporting from social media feedback. *Online Social Networks and Media, 45*, 100295. https://doi.org/10.1016/j.osnem.2024.100295

[14] Cantini, R., Cosentino, C., Marozzo, F., Talia, D., & Trunfio, P. (2025). Harnessing prompt-based large language models for disaster monitoring and automated reporting from social media feedback. *Online Social Networks and Media, 45*, 100295. https://doi.org/10.1016/j.osnem.2024.100295

adapted to meet the specific informational needs of different stakeholders—ranging from local field responders to national-level decision-makers[15][16].

- **Conversational Data Access[17][18]:** By enabling natural language querying of structured and validated data repositories, LLMs significantly lower the barrier to accessing critical information. Non-technical personnel in the field can interact with decision-support systems using informal, domain-specific language (e.g., "Where are the nearest operational medical facilities?"), and receive timely, context-aware responses.
- **Communication Automation:** LLMs can generate public-facing communications[19], such as evacuation alerts or safety instructions, that are both linguistically accurate and contextually sensitive. This reduces the cognitive and operational burden on communication officers, particularly during peak crisis periods.
- **Multilingual and Cross-Cultural Capabilities[20]:** Many LLMs support multilingual outputs and can be fine-tuned to respect regional linguistic nuances, facilitating more inclusive communication strategies in multilingual or cross-border disaster scenarios.

The integration of LLMs into disaster response frameworks holds the potential to enhance situational awareness, accelerate decision-making processes, and reduce informational bottlenecks. When coupled with validated data pipelines and geospatial intelligence systems, LLMs can function as intelligent mediators[21] between raw data and strategic action—delivering insights in a form that is immediately usable and operationally relevant.

As such, LLMs are not merely assistive tools but are rapidly becoming essential components of next-generation crisis informatics and digital emergency management systems.

Key Milestones in NLP: From BERT to GPT

Key Milestones in NLP: From BERT to GPT in Disaster Response

The evolution of Natural Language Processing (NLP) has significantly enhanced the capabilities of disaster response systems. From the introduction of BERT to the advancements in GPT models, these technologies have transformed how emergency information is processed and utilized. This review explores the progression of NLP models and their applications in disaster response, highlighting recent research and implementations by various organizations.

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[15] Sufi, F. K. (2024). A systematic review on the dimensions of open-source disaster intelligence using GPT. *Journal of Economy and Technology, 2*, 62–78. https://doi.org/10.1016/j.ject.2024.03.004

[16] Rolla, J., Khuller, A., An, K., Emberson, R., Fielding, E., Schultz, L., & Miner, K. (2025). Satellite-aided disaster response. *AGU Advances*. https://doi.org/10.1029/2024AV001395

[17] Weerasinghe, K., Janapati, S., Ge, X., Kim, S., Iyer, S., Stankovic, J. A., & Alemzadeh, H. (2024). Real-Time Multimodal Cognitive Assistant for Emergency Medical Services. *arXiv preprint*. https://arxiv.org/abs/2403.06734

[18] Chan, H.-Y., & Tsai, M.-H. (2019). Question-answering dialogue system for emergency operations. *International Journal of Disaster Risk Reduction, 41*, 101313. https://doi.org/10.1016/j.ijdrr.2019.101313

[19] Cantini, R., Cosentino, C., Marozzo, F., Talia, D., & Trunfio, P. (2025). Harnessing prompt-based large language models for disaster monitoring and automated reporting from social media feedback. *Online Social Networks and Media, 45*, 100295. https://doi.org/10.1016/j.osnem.2024.100295

[20] Sufi, F. K. (2024). A systematic review on the dimensions of open-source disaster intelligence using GPT. *Journal of Economy and Technology, 2*, 62–78. https://doi.org/10.1016/j.ject.2024.03.004

[21] Bhowmik, R. T., Jung, Y. S., Aguilera, J. A., Prunicki, M. M., & Nadeau, K. (2023). A multi-modal wildfire prediction and early-warning system based on a novel machine learning framework. *Journal of Environmental Management, 341*, 117908. https://doi.org/10.1016/j.jenvman.2023.117908

Introduced by Google in 2018, BERT (Bidirectional Encoder Representations from Transformers) marked a significant advancement in NLP by enabling models to understand the context of words in a sentence bidirectionally. This capability improved tasks like sentiment analysis, question answering, and text classification[22] .

In disaster response, BERT has been utilized to analyze social media data, providing insights into public sentiment and information dissemination during crises. For instance, studies have demonstrated BERT's effectiveness in classifying disaster-related tweets, aiding in real-time situational awareness[23] .

OpenAI's GPT series, starting with GPT-2 and advancing to GPT-4, introduced models capable of generating coherent and contextually relevant text. These models have been fine-tuned for various applications, including disaster response.

GPT-4 has been employed to develop chatbots that assist in disaster preparedness and response. For example, a multilingual disaster bot using GPT-4 and LangChain[24] was created to help users access FEMA guidelines during emergencies.

Social media platforms serve as critical sources of real-time information during disasters. Models like QuakeBERT have been developed to classify and filter earthquake-related microblogs, enhancing the accuracy of impact assessments[25].

Similarly, DistilBERT[26], a lighter version of BERT, has been applied to classify disaster-related tweets efficiently, achieving high accuracy while reducing computational requirements.

DistilBERT[27], introduced by Sanh et al. (2019), is a distilled version of the BERT model, designed to be smaller, faster, and more efficient while retaining a significant portion of BERT's performance capabilities. Its streamlined architecture has made it particularly appealing for applications in disaster response, where rapid processing and deployment are crucial.

DistilBERT achieves a 40% reduction in model size and a 60% increase in speed compared to BERT, while retaining 97% of its language understanding capabilities. This efficiency makes it suitable for deployment in resource-constrained environments, such as during disaster scenarios where computational resources may be limited.

DistilBERT yields to comparable performance on downstream tasks. Comparison on downstream tasks: IMDb (test accuracy) and SQuAD 1.1 (EM/F1 on dev set). D: with a second step of distillation during fine-tuning.

Model	IMDb (acc.)	SQuAD (EM/F1)
BERT-base	93.46	81.2/88.5
DistilBERT	92.82	77.7/85.8
DistilBERT (D)	-	79.1/86.9

DistilBERT is significantly smaller while being constantly faster. Inference time of a full pass of GLUE task STS-B (sentiment analysis) on CPU with a batch size of 1.

Model	# param. (Millions)	Inf. time (seconds)
ELMo	180	895
BERT-base	110	668
DistilBERT	66	410

[22] https://www.ibm.com/think/insights/how-bert-and-gpt-models-change-the-game-for-nlp

[23] https://arxiv.org/abs/2108.10698

[24] https://towardsdatascience.com/researching-a-multilingual-fema-disaster-bot-using-langchain-and-gpt-4-4591f26d8dcd

[25] https://arxiv.org/abs/2108.10698

[26] https://www.etasr.com/index.php/ETASR/article/view/7232

[27] https://arxiv.org/abs/1910.01108

In a study focusing on classifying disaster-related tweets, DistilBERT achieved an average training accuracy of 92.42% and a validation accuracy of 82.11%, demonstrating its effectiveness in real-time disaster monitoring[28].

DistilBERT has been effectively utilized in multilingual disaster bots, aiding in the dissemination of emergency information across different languages. Its adaptability extends to multimodal applications, where it can be integrated with other models to process various data types, enhancing the comprehensiveness of disaster response systems.

While DistilBERT maintains high performance in many tasks, it may underperform in more complex applications compared to larger models like BERT or GPT-3, particularly in tasks requiring deep contextual understanding.

DistilBERT's general-purpose training may not capture domain-specific nuances essential for certain disaster scenarios. Fine-tuning on specialized datasets is necessary to enhance their performance in specific contexts[29].

Recent studies[30] have combined DistilBERT with optimization algorithms like the Hunger Games Search (HGS) to improve crisis event detection. This hybrid approach has shown superior performance in identifying relevant disaster-related information from social media.

In assessing flood severity, DistilBERT has been integrated with Named Entity Recognition (NER) to extract location information from social media posts. This combination achieved 99% accuracy in text classification and 89% in location identification, facilitating timely and precise disaster response[31].

Accurate location information is vital for effective disaster response. Geo-knowledge-guided GPT models have been introduced to extract detailed location descriptions from social media posts, outperforming traditional Named Entity Recognition tools[32].

These models have demonstrated significant improvements in identifying locations mentioned in tweets during disasters like Hurricane Harvey, facilitating quicker response times.

GPT models have been integrated into decision support systems to assist emergency managers. For instance, DisasterResponseGPT[33] leverages GPT-4 to generate actionable plans based on scenario descriptions, streamlining the planning process during emergencies. Additionally, AI assistants powered by GPT-4 have been developed to interpret complex flood risk data, making it accessible to both decision-makers and the public.

Various organizations have adopted NLP models to enhance disaster response. The American Red Cross, for example, has developed chatbots using GPT models to provide timely information during emergencies[34].

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28 https://www.etasr.com/index.php/ETASR/article/view/7232

29 https://www.mdpi.com/2227-7390/10/3/447

30 https://www.mdpi.com/2227-7390/10/3/447

31 https://link.springer.com/chapter/10.1007/978-981-99-0047-3_34

32 https://github.com/geoai-lab/Geo-knowledge-guided-GPT-models-for-disaster-response

33 https://arxiv.org/abs/2306.17271

34 https://towardsdatascience.com/researching-a-multilingual-fema-disaster-bot-using-langchain-and-gpt-4-4591f26d8dcd

Furthermore, academic institutions like the University at Buffalo have conducted research on utilizing GPT models for extracting critical information from social media, contributing to more effective emergency responses[35].

The progression from BERT to GPT models has significantly impacted disaster response strategies. By enabling real-time analysis of social media, accurate location extraction, and efficient decision-making support, these NLP advancements have improved the responsiveness and effectiveness of emergency services. Continued research and implementation of these technologies promise further enhancements in managing and mitigating the impacts of disasters.

Fine-tuning and Adaptability of LLMs

Large Language Models (LLMs) have revolutionized various domains by enabling machines to understand and generate human-like text. In disaster response management, the adaptability and fine-tuning of LLMs play a crucial role in processing vast amounts of unstructured data, facilitating real-time decision-making, and enhancing situational awareness. This review explores the current state-of-the-art (SoTA) in fine-tuning LLMs for disaster response, highlighting methodologies, applications, and future directions.

Traditional text classification models often rely on single-label classification, which may not capture the multifaceted nature of disaster-related information. To address this, researchers have developed instruction fine-tuned LLMs capable of multi-label classification. For instance, the CrisisSense-LLM[36] integrates instruction fine-tuning to classify disaster-related tweets into multiple categories simultaneously, such as event type, informativeness, and human aid involvement. This approach enhances the utility of social media data for situational awareness during disasters.

Active Learning (AL) is a machine learning paradigm where the model selectively queries the most informative data points for labelling, thereby improving learning efficiency. In the context of disaster response, combining AL with fine-tuning has shown promising results. A study compared keyword filtering, generic fine-tuning, and AL-based fine-tuning approaches for identifying disaster-related tweets. The findings indicated that a RoBERTa[37] model fine-tuned with generic data and further trained using AL outperformed other methods, achieving high classification performance with minimal labelling effort.

Fine-tuning large models can be computationally intensive. To mitigate this, parameter-efficient fine-tuning methods like Low-Rank Adaptation (LoRA) and Representation Fine-Tuning (ReFT) have been proposed[38]. LoRA introduces low-rank matrices to the model, allowing efficient fine-tuning with reduced computational resources. ReFT, on the other hand, modifies a small fraction of the model's representations, steering model behaviours towards specific tasks without updating the entire model. These techniques enable the deployment of LLMs in resource-constrained disaster scenarios.

Developing effective plans of action during disasters is time-sensitive. LLMs can expedite this process through in-context learning. The DisasterResponseGPT[39] model leverages LLMs to generate valid plans of action by incorporating disaster response guidelines into the initial prompt. Users input scenario descriptions and receive actionable plans, which can be refined based on

[35] https://www.buffalo.edu/news.host.html/content/shared/university/news/ub-reporter-articles/stories/2023/12/chat-gpt-disasters.detail.html

[36] https://arxiv.org/abs/2406.15477

[37] https://arxiv.org/abs/2408.09914

[38] https://arxiv.org/pdf/2106.09685v1/1000

[39] https://arxiv.org/abs/2306.17271

feedback. This approach accelerates plan development and allows real-time adjustments during disaster response operations.

Assessing damage post-disaster is crucial for effective resource allocation. The integration of Large Vision Language Models (LVLMs) offers a novel solution. The DisasTeller[40] framework employs multiple LVLM agents, coordinated by GPT-4, to automate tasks such as on-site assessment, emergency alerts, and recovery planning. This multi-agent system streamlines disaster response activities, reduces human execution time, and optimizes resource distribution.

While fine-tuning LLMs for disaster response has shown significant promise, challenges remain. Ensuring model robustness to distribution shifts is critical, as fine-tuned models may underperform when exposed to data from different distributions. Techniques like interpolating fine-tuned model weights with original model weights have been proposed to enhance out-of-distribution performance. Future research should focus on developing domain-specific fine-tuning datasets, improving model interpretability, and exploring hybrid models that combine textual and visual data for comprehensive disaster analysis.

Challenges in Applying LLMs in Disaster Scenarios

One of the primary challenges lies in the mismatch between the training data and the target disaster scenario. Most LLMs are pre-trained on general-purpose corpora such as books, web pages, or Wikipedia. Disaster contexts often involve:

- Noisy, multilingual social media text
- Abrupt changes in vocabulary (e.g., hashtags like #HarveyAid)
- Unstructured, situational data with local jargon

This "distribution shift" can drastically degrade model performance unless the LLM is fine-tuned with domain-specific data — a costly and often infeasible process during an active emergency.

Real-time disaster response demands fast and efficient processing of data streams. However:

- Large LLMs like GPT-4 require significant computational power, often available only in high-end servers or cloud environments.
- In remote or damaged areas, infrastructure for cloud access may be unreliable.
- Edge deployment (e.g., using mobile devices or low-power machines) is impractical without model compression or distillation techniques like LoRA or DistilBERT.

LLMs are known to "hallucinate" — i.e., generate plausible-sounding but false or misleading information. In disaster contexts, this can have critical consequences:

- Incorrect medical advice
- Misdirected emergency response
- Propagation of rumours or false alerts

For example, if a user asks an LLM for the location of emergency shelters and it generates incorrect data, it could cause harm or loss of life. Mitigating this risk requires validation layers and expert oversight.

LLMs may reflect inherent biases from their training data — e.g., geographic, linguistic, or socio-economic biases. This is especially problematic in disasters that affect marginalized communities:

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[40] https://arxiv.org/html/2502.05957v1

- Language models may favour English content, neglecting non-English speakers.
- Urban-centric data may leave rural disaster zones underrepresented.
- Aid recommendations may reflect cultural biases, affecting effectiveness.

Bias mitigation in crisis situations is an open research problem that requires proactive auditing and inclusive training practices.

Disaster scenarios often involve sensitive personal data, including health information, geographic coordinates, and private communications. LLMs processing such data must adhere to:

- Privacy laws (e.g., GDPR, HIPAA)
- Ethical guidelines for informed consent
- Secure handling and storage mechanisms

This is complicated by the often-chaotic nature of emergencies, where consent and oversight may be limited.

Emergency responders and humanitarian agencies need transparent, explainable models. However, LLMs are often "black boxes", offering little clarity on:

- Why a certain decision or recommendation was made
- How confident the model is in its output

Low interpretability hinders trust and adoption by domain experts, especially when decisions have life-or-death consequences.

Disasters generate heterogeneous data: images (flood damage), sensor data (seismic activity), satellite imagery, and texts (reports, tweets). While multimodal models (e.g., GPT-4V, LLaVA[41]) are emerging, current LLMs still struggle with:

- Integrating visual and textual inputs seamlessly
- Accurately interpreting noisy or low-resolution images
- Synchronizing temporal and spatial data streams

This limits their applicability for end-to-end situational analysis.

While LLMs present powerful opportunities for disaster response management, their effective deployment is constrained by several significant challenges:

- The need for domain-specific adaptation
- Computational limitations in resource-strained environments
- Risks of misinformation and ethical misuse
- Bias and fairness in high-stakes decision-making

Addressing these issues requires collaborative efforts between AI researchers, humanitarian organizations, and policymakers. As a starting point, SIREN will use the Dedoctive platform from Collaboration Tools Ltd to generate trustworthy LLM responses using structured workflows, drawing only on verified data sources and including hyperlinks to detailed provenance that can be further explored visually. Future directions should focus on robust fine-tuning techniques, model

[41] https://llava-vl.github.io/

interpretability, bias auditing, and the safe, ethical application of LLMs in real-time, high-risk scenarios.

Advancing Decision Support Optimization in Disaster Management

Disaster management has evolved significantly in recent years, driven by advances in data analytics, optimization, and artificial intelligence. However, the increasing frequency and severity of disasters necessitate continued innovation to manage complexity, uncertainty, and dynamic decision environments. We outline key areas of innovation in decision support systems (DSS), emphasizing multi-objective optimization, adaptive planning, real-time data integration, and advanced resource coordination tools.

State of the Art in DSS for Disaster Management

Contemporary decision support systems in disaster management are increasingly data-driven and integrated with real-time communication platforms. These systems aim to facilitate situational awareness, support planning, and optimize resource deployment. However, despite significant developments, such as agent-based modelling, online optimization, simulation tools, and GIS-based platforms, many existing DSS solutions fall short in terms of adaptability, robustness under uncertainty, and user-friendly integration with field operations (Shiri et al 2024)[42].Our proposed innovations go beyond the current state of the art by emphasizing multi-layered, intelligent systems capable of real-time learning and coordination under dynamic conditions.

Multi-objective Optimization

Disaster management inherently involves trade-offs between conflicting objectives, minimizing response time, maximizing resource utilization, minimizing economic or environmental impact, maximizing delivered goods in a limited time while maximizing network accessibility by removing debris from road segments. Multi-objective optimization (MOO) frameworks allow for explicit modelling of these trade-offs. Recent research has focused on addressing simultaneous distribution of relief items and road restoration operations (Akbari and Sayarshad 2021)[43]. However, in this research a single relief distribution and single road restoration team are considered. Further research is required to address the more realistic case where multiple relief distribution and road recovery teams work together to maximize delivery of relief items in a limited time while restoring the damaged segments of the road networks. Our framework builds upon these approaches, introducing real-time MOO capabilities for the simultaneous relief distribution and debris clearance within multiple planning days, enabling decision-makers to explore Pareto-optimal solutions aligned with policy and operational goals.

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[42] Shiri, D., Akbari, V., & Hassanzadeh, A. (2024). The Capacitated Team Orienteering Problem: An online optimization framework with predictions of unknown accuracy. *Transportation Research Part B: Methodological*, *185*, 102984.

[43] Akbari, V., & Sayarshad, H. R. (2022). Integrated and coordinated relief logistics and road recovery planning problem. *Transportation Research Part D: Transport and Environment*, *111*, 103433.

Real-Time Case Coordination and Adaptive Planning

Disaster environments are inherently dynamic. Traditional planning approaches often rely on static assumptions, which rapidly become obsolete during unfolding crises (Shiri et al 2020)[44]. Our system proposes adaptive planning modules that incorporate real-time feedback loops. These modules use reinforcement learning and scenario-based optimization to adjust task priorities and resource assignments in response to evolving needs, road closures, or supply shortages. This capability enhances responsiveness and reduces coordination lag, ultimately improving outcome efficiency and reducing loss.

AI-Infused Workforce and Equipment Management

Effective deployment of personnel and equipment is crucial for efficient disaster response. Existing systems often struggle with capturing the dynamic availability, location, and suitability of resources. Our approach integrates AI-driven scheduling and routing algorithms with real-time data streams from field devices, allowing for continuous re-optimization of workforce tasks and equipment usage (Lee and Lee 2021)[45]. Graph-based representations of resource dependencies and location-aware scheduling improve coordination and reduce idle time. Additionally, AI models trained on historical disaster data improve predictive allocation, contributing to both operational efficiency and staff safety.

Needs and Resource Mapping with Graph Databases

Mapping resource needs to available supplies requires integrating diverse datasets, geographic, demographic, inventory, infrastructure, and real-time incident reports. Traditional relational databases fall short in capturing complex interdependencies. Our system utilizes graph databases, such as Neo4j, to represent and traverse relationships among affected areas, logistics hubs, supply items, and stakeholders (Mu et al 2024)[46]. This structure enables rapid querying, priority assessment, and classification of needs. Moreover, it facilitates visual mapping of critical paths for aid delivery and supports decision-making in resource-constrained scenarios.

Advanced Debris Management Models

Post-disaster debris significantly hinders mobility and recovery efforts. Many debris management models simplify the problem by assuming static capacities and homogeneous teams (Akbari et al, 2021)[47]. Our contribution is a real-time debris clearance optimization module that considers multiple task teams, for road recovery and relief distribution activities. The conditions of the road network dynamically changes as the road restoration operations takes place and our approach incorporates this in a multi-period setting were the repaired road segments in one period, are added to the traversable roads for the next planning periods. Moreover, these models also incorporate temporal priorities, for example, clearing paths to hospitals first, as delivering relief items to them can benefit

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[44] Shiri, D., Akbari, V., & Salman, F. S. (2020). Online routing and scheduling of search-and-rescue teams. *OR Spectrum*, *42*, 755-784.

[45] Lee, H. R., & Lee, T. (2021). Multi-agent reinforcement learning algorithm to solve a partially-observable multi-agent problem in disaster response. *European Journal of Operational Research*, *291*(1), 296-308.

[46] Mu, H., Wu, P., & Su, W. (2024). Construction of knowledge graph for emergency resources. *International Journal of Intelligent Systems*, *2024*(1), 6668559.

[47] Akbari, V., Shiri, D., & Salman, F. S. (2021). An online optimization approach to post-disaster road restoration. *Transportation research part B: methodological*, *150*, 1-25.

the entire system significantly. The integration of sustainability goals adds an environmental dimension, ensuring alignment with long-term recovery strategies.

Integration with Real-Time Spatial Asset Tracking

Asset tracking technologies, RFID, GPS, and IoT devices, have matured significantly, offering an opportunity to tightly integrate real-time location data into DSS (Ambrosia et al 2021)[48]. We propose embedding spatial asset tracking into the core of our optimization models, enabling a live operational picture of vehicle positions, inventory levels, and personnel movements. This allows for automated detection of delays, prediction of potential bottlenecks, and seamless adaptation of routing and resource plans. Coupled with MOO algorithms, this integration maximizes delivery reliability under dynamic constraints.

Innovations in Wildfire Suppression Coordination

While GIS-based wildfire tools such as ESRI's ArcGIS suite support hazard mapping and visualization, they often lack advanced optimization capabilities. Our approach introduces semi-automated coordination algorithms into wildfire suppression planning. These algorithms evaluate trade-offs among fire line construction, resource concentration, and risk exposure (Avci et al 2024)[49]. When integrated with meteorological data and topography, they support predictive fire spread modelling and anticipatory response. Our goal is to embed these tools into industrial partner platforms, enhancing strategic decision-making and operational control during wildfire crises.

Semantic Geo-Spatial Intelligence

State of the Art in Urban Profiling and Change Detection

The field of Semantic Geo-Spatial Intelligence has undergone rapid evolution, particularly in the context of disaster preparedness and response. Emerging technologies in geospatial artificial intelligence (Geo-AI), crowdsourced geo-information, and high-frequency remote sensing are now central to urban profiling and change detection for disaster risk reduction and humanitarian response. Within the scope of the SIREN project, these advancements enable a paradigm shift in managing and mitigating the impacts of natural catastrophes such as earthquakes, floods, and wildfires.

Modern urban disasters demand intelligent spatial planning frameworks capable of integrating diverse and real-time spatial data to support rapid, informed decision-making. Geospatial big data analytics allow for the continuous monitoring of urban morphology, infrastructure status, and population dynamics—facilitating the development of semantic 3D city models for scenario simulation and damage assessment (Jing et al., 2023; Fauzi, 2024).

Crowdsourcing initiatives like Geo-Wiki and Mapillary have democratized access to local-level spatial intelligence, offering real-time insights from affected populations. During the 2023 Türkiye earthquakes, volunteer-contributed geodata enabled platforms like Başarsoft's Earthquake Aid Portal to map live assistance calls from social media, significantly improving search-and-rescue

[48] Ambrosia, V. G., Sullivan, D. V., & Buechel, S. W. (2011). Integrating sensor data and geospatial tools to enhance real-time disaster management capabilities: Wildfire observations.

[49] Avci, M. G., Avci, M., Battarra, M., & Erdoğan, G. (2024). The wildfire suppression problem with multiple types of resources. *European Journal of Operational Research*, *316*(2), 488-502.

coordination and access to affected areas. Such systems exemplify the potential of participatory urban profiling in disaster settings.

Furthermore, commercial platforms contribute essential capabilities. Urban Hawk's integration of LiDAR, radar, and video analytics produces dynamic semantic models of built environments, supporting real-time risk assessment and operational planning. Descartes Labs employs machine learning on satellite imagery to detect infrastructure damage and environmental change at scale—an approach aligned with the situational awareness needs of disaster scenarios. Similarly, Google Earth Engine and xView2 have demonstrated value in post-disaster building damage detection using high-resolution satellite imagery and ML-based classification.

The analytical processing of spatial data has become increasingly sophisticated with the adoption of Spatial OLAP, spatio-temporal data cubes, and graph-based geospatial inference systems (Bimonte, 2016). These methods allow emergency managers to correlate multivariate spatial datasets—e.g., hospital capacity, shelter access, road network operability—into decision-ready intelligence during the acute response phase.

In the SIREN architecture, urban profiling and change detection form the backbone of simulation-supported decision-making. Semantic simulation within geo-specific environments facilitates the modelling of rubble clearance, utility outages, and emergent hazards. By enabling the continuous integration of UAV-acquired imagery, VGI, and IoT sensor streams, SIREN supports a living digital twin of disaster-affected zones. This twin can model the secondary and tertiary effects of interventions, such as road reopening or network restoration, allowing responders to optimize actions under uncertainty.

However, technical challenges persist. These include data fragmentation, heterogeneous ontologies, and inconsistent temporal granularity, all of which complicate cross-agency collaboration and real-time data fusion. SIREN seeks to overcome these through semantic interoperability protocols and AI-supported data verification pipelines that transform unstructured data (e.g., social media posts, SMS, volunteer reports) into structured situational intelligence. The system's natural language understanding layer further allows decision-makers to query spatial data semantically, enhancing usability in high-pressure environments.

The integration of predictive analytics enables forward-looking urban profiling, offering forecasts of population displacement, infrastructure stress, and spatial accessibility—essential for pre-positioning resources and routing first responders. As demonstrated in Türkiye, more than 80% of rescue operations conclude within the first 48 hours; thus, speed and accuracy in spatial understanding are paramount (Shiri et al., 2020).

Dedoctive Technology: Innovation Description

The Dedoctive technology provided to SIREN by Collaboration Tools Ltd is a unique AI innovation that wraps LLM models to generate trustworthy LLM responses using structured workflows, drawing only on verified data sources and including hyperlinks to detailed provenance that can be further explored visually.

Dedoctive contributes to the SIREN project's objectives by offering innovative capabilities that enhance the trustworthiness and utility of AI-generated responses in high-risk scenarios like disaster response.

Dedoctive addresses the challenge of generating trustworthy LLM responses by overcoming the limitations of standard AI techniques such as Retrieval-Augmented Generation (RAG). Standard

RAG can produce inaccurate responses due to misinterpretation, missing information, or conflicting details, and may lack trustworthiness because information is unverified. Dedoctive ensures answers are derived solely from the provided data by converting document collections into a comprehensive knowledge model and supplying only relevant "facts" to the AI model for interpretation. This ensures the LLM uses only the provided knowledge, not other potentially unverifiable information or hallucinations.

A key aspect of Dedoctive is its use of structured workflows. It provides composable workflows built on BPMN (Business Process Model and Notation), which is a standard for describing complex business processes. These workflows can incorporate user input, scripts, and AI agents, and are available as Google/A2A compliant agents. Dedoctive uses a unique combination of agentic and deterministic workflows.

To ensure responses are based on verified data sources, Dedoctive employs a dual-layer LLM pipeline to create a sophisticated knowledge model from various data sources like websites and documents. This model serves as the basis for retrieving relevant information.

Dedoctive builds trust and reliability by including provenance with hyperlinks. Each answer includes valid hyperlinks to the source facts, allowing users to easily verify the information. This links the LLM's response back to the knowledge facts and their original source documents.

Furthermore, Dedoctive allows users to visually explore the knowledge used to generate a response. The DedoctiveUI provides a 'response knowledge map' that graphically reveals how a statement in the answer is connected through knowledge model entities to the source document elements. This feature promotes a deeper understanding of complex information.

These capabilities, such as the advanced knowledge modeling, robust provenance, and visual exploration features, make Dedoctive a valuable platform for SIREN to deliver accurate, reliable, and verifiable information in critical real-time disaster response scenarios.

Urban Hawk Technology: Innovation Description

Urban Hawk Technology demonstrates a pivotal innovation at the convergence of urban animal rescue and public health surveillance, with transformative implications for zoonotic disease management in high-density urban settings. Originally designed for animal rescue operations, the Hawk Data Pro system has evolved into a passive surveillance tool for tracking rabies outbreaks in Indian cities, illustrating how adaptable geo-spatial intelligence can enhance public health resilience in fragile urban ecosystems (Vanak et al., 2022; 2023).

The system integrates citizen reports, veterinary assessments, and spatially-anchored alerts to facilitate real-time epidemiological surveillance. This capability is especially crucial in post-disaster scenarios, where the breakdown of infrastructure and displacement of both human and animal populations can increase zoonotic disease risks. In such settings, semantic urban profiling enabled by platforms like Hawk Data Pro provides a real-time view of emerging public health threats, supporting targeted interventions and spatial prioritization of resources.

In the context of the SIREN project, this approach aligns with the broader goals of enhancing situational awareness and health logistics through semantic data integration and predictive simulation. For instance, the ability to simulate and visualize the spread of vector-borne or contact-transmissible diseases—such as rabies or leptospirosis—in the aftermath of floods or earthquakes is essential for preventing secondary health crises. Urban Hawk’s model of rapid field diagnostics and decentralized data capture serves as a reference case for embedding health surveillance within urban digital twins that inform disaster response.

The Hawk Data Pro framework further exemplifies how semantic interoperability across human health, animal health, and environmental data domains supports a One Health paradigm—a principle that is central to SIREN's systemic risk assessment framework. Integrating these insights into SIREN's disaster simulation environment enables the platform to support public health decision-making, including vaccination campaign planning, disease containment zone mapping, and resource pre-positioning.

Nevertheless, the widespread adoption of such integrated surveillance systems faces significant challenges. These include ensuring equitable access to digital tools, maintaining data quality across sources, and establishing inter-sectoral governance structures. Addressing these issues will be critical to replicating and scaling Urban Hawk's capabilities across other urban contexts and hazard scenarios.

3D Modelling and Semantic Fusion

3D modeling and semantic fusion have emerged as transformative tools in contemporary urban planning and disaster management, providing multi-dimensional insights that support precise and responsive decision-making. Within the scope of the SIREN project, these technologies are leveraged to build real-time, semantically enriched digital twins of disaster-affected environments, enabling dynamic monitoring, impact assessment, and scenario simulation in critical situations.

The integration of semantic, spatial, and temporal dimensions into urban models allows for operational readiness, coordination of emergency logistics, and simulation of cascading effects triggered by natural hazards such as earthquakes, floods, or wildfires. These models underpin SIREN's strategy to provide situational awareness and facilitate anticipatory action through simulation-aided decision support.

A key advancement in this domain is the shift from purely geometric models to semantically enriched digital twins that not only capture the physical structure of urban environments but also embed information about function, structural status, occupancy, and emergency accessibility. Vinasco-Alvarez et al. underscore the importance of data-driven fusion techniques to develop 3D and 4D semantic city models, which are essential for tracking urban transformations across time and supporting disaster-resilient planning. These models enable interoperability across domains such as search and rescue routing, debris clearance optimization, and public health logistics.

Emerging commercial technologies increasingly support this vision. Bentley Systems' OpenCities Planner enables semantic layering on city-scale 3D models for emergency communication and infrastructure status tracking. Similarly, Esri's ArcGIS Urban offers procedural modeling with semantic rule engines that simulate zoning breakdowns, population distribution, and damage potential under disaster conditions. These platforms exemplify how semantic 3D modeling is becoming integral to responsive disaster governance.

Subsurface modeling is gaining prominence with the realization that underground infrastructure—utilities, shelters, and collapsed zones—plays a critical role in disaster response. Solutions like Leapfrog Works by Seequent and Bentley's gINT integrate geotechnical data into 3D frameworks, supporting rapid risk assessment and underground access planning. Research by Hao et al. and

Zhang et al. highlights the need for such geological data fusion to inform rescue strategies and post-disaster rebuilding.

Semantic interoperability frameworks, such as CityGML and its evolving successor CityJSON, facilitate standardization in representing complex urban systems in emergency contexts. These formats enable the structuring of thematic layers—buildings, roads, infrastructure—with attributes such as structural integrity, safe access points, or emergency capacity. Chaturvedi and Kolbe emphasize the ability of semantic rules to capture dependencies such as access constraints in rubble zones or power connectivity to shelters. Zahid et al. and Beil et al. demonstrate how semantically-rich models support multi-scenario response planning and aid coordination among first responders, municipalities, and humanitarian organizations.

Technological progress in data acquisition and processing, particularly through UAV-based LiDAR and photogrammetry, has accelerated the automation of 3D building reconstruction in disaster zones. Platforms such as Pix4D and Autodesk ReCap automate point cloud generation, while software like FME enables semantic tagging for hazard zones and functional annotations such as triage capacity or shelter designation. Studies by Jayaraj, Zheng, and others show how these methods support damage classification, evacuation route planning, and utility restoration strategies. High-resolution models also enable the mapping of debris fields, hazard propagation analysis, and structural collapse simulations, as illustrated by the works of Prieto and Xue.

Despite these advancements, operationalizing 3D semantic models in disaster contexts remains constrained by challenges in data standardization, software interoperability, and real-time model updates. The lack of consistent support across platforms hampers the seamless deployment of these models in live response workflows. Moreover, maintaining data consistency across Level of Detail (LoD) hierarchies—particularly in hybrid models that combine above-ground, underground, and post-disaster derived data—remains a technical hurdle. As Biljecki, Agugiaro, and Billen point out, these gaps must be addressed through robust ontologies, harmonized emergency data protocols, and scalable APIs to unlock the full potential of 3D semantic city modeling in SIREN's disaster management ecosystem.

UID and Spatial Data Linking for Action Planning

The integration of Unique Identifiers (UIDs) and spatial data linking constitutes a critical enabler in disaster-responsive action planning, particularly within the realms of infrastructure management, humanitarian logistics, and emergency coordination. In the context of the SIREN project, this framework enhances the capacity to fuse heterogeneous datasets—spanning from satellite imagery and IoT sensor streams to social vulnerability indices—into coherent, decision-ready information systems that support rapid and adaptive response strategies.

UIDs serve as key components for ensuring semantic and spatial coherence across otherwise fragmented datasets. Their function as relational anchors between socio-demographic attributes, asset inventories, hazard exposures, and geolocated infrastructure enables advanced network analysis and real-time coordination in crisis situations. Bensmann et al. emphasize the need for a robust spatial data infrastructure (SDI) that bridges social science, geoinformatics, and emergency operations, promoting effective data sharing and high-resolution situational awareness across agencies and platforms (Bensmann et al., 2020).

In practical disaster management scenarios, UID-enabled systems enhance tracking of shelters, temporary health facilities, blocked roads, and service disruptions. For instance, RapidDeploy and

Esri's Disaster Response Program deploy UID-linked dashboards that consolidate GIS data, emergency call logs, and sensor networks to support unified command structures. These platforms illustrate how UID frameworks can transform response efficiency through precise geospatial referencing of critical assets and events.

The relationship between transportation infrastructure and disaster resilience is deeply tied to spatial accessibility and real-time operability. Liang and Li's analysis of transport-related spillover effects aligns with the SIREN objective of evaluating infrastructure vulnerabilities and recovery potential in affected areas (Liang & Li, 2020). By tagging key transport nodes and links with persistent UIDs, emergency planners can model multi-modal routing, prioritize repair efforts, and anticipate bottlenecks under disrupted network conditions.

Incorporating UID frameworks also improves the spatial integration of diverse transport modalities during emergencies. Risimati et al. highlight the success of integrating non-motorized and public transit systems for urban resilience—an approach mirrored in SIREN's ambition to merge last-mile delivery, SAR team routing, and volunteer logistics using unified geospatial references (Risimati et al., 2021). Commercial systems like HERE Location Services and TomTom Traffic Data enable this integration in real time, offering API-accessible UID-linked layers for road segments, congestion points, and route accessibility.

Furthermore, the use of UIDs allows for holistic analyses of indirect systemic effects—such as post-disaster supply chain reconfiguration or displacement-driven demand surges. Shen et al. underscore the critical role of transport systems in harmonizing land use, service accessibility, and logistics flows (Shen et al., 2024). In SIREN's operational environment, these insights are leveraged to balance emergency service deployment with long-term recovery planning and spatial equity.

Challenges in UID integration remain significant. These include the need for interoperable schemas across jurisdictions, consistency in ID assignment protocols, and mechanisms for real-time updates in dynamic environments. Condeço-Melhorado et al. emphasize that network and spillover effects cannot be accurately assessed without consistent node and link identifiers, reinforcing the need for structured geospatial ontologies and cross-agency data governance (Condeço-Melhorado et al., 2014).

By embedding UID-based spatial linkages into its simulation architecture, SIREN not only advances disaster response capabilities but also sets a precedent for resilient urban governance frameworks. The ability to trace, simulate, and optimize interdependencies between people, infrastructure, and resources under stress is indispensable for managing the complexity of modern disasters.

Integration with Transport Infrastructure Modelling (Road & Rail)

The integration of transport infrastructure modeling—encompassing both road and rail systems—plays a critical role in building resilient and adaptive urban environments, particularly in the context of disaster preparedness and emergency response. Within the SIREN project, transport modeling is fundamental for simulating access constraints, evaluating evacuation routes, and coordinating the rapid deployment of aid and emergency services following disruptive events such as earthquakes, floods, or wildfires.

A key advancement in this field is the development of ontologies specifically designed to support smart, disaster-aware transportation frameworks. Zhu and Chowdhury propose the creation of integrated transportation ontologies that extend beyond traffic management to encompass the full spectrum of transportation infrastructure, including emergency accessibility, damage risk profiling, and multimodal resilience (Zhu & Chowdhury, 2019). For SIREN, such ontologies serve as semantic anchors for aligning real-time data inputs—ranging from blocked routes to bridge integrity—with decision-support systems.

The incorporation of Intelligent Transportation Systems (ITS) further enhances the responsiveness of urban transit networks in emergencies. These systems employ communication and control technologies to enable real-time traffic monitoring, adaptive signal control, and predictive congestion management. In disaster contexts, ITS platforms like Kapsch TrafficCom or Siemens Mobility have been deployed to maintain continuity of mobility services, redirect flows around impacted zones, and facilitate coordination between emergency fleets and public transport systems (Parrado & Donoso, 2015).

Geographic Information Systems (GIS) are equally indispensable for transport accessibility analysis during and after disaster events. Tools such as Esri's Network Analyst and HERE's Routing APIs enable geospatial assessment of route viability, travel-time disruptions, and infrastructure bottlenecks. Ford et al. developed a GIS-based tool capable of performing multimodal transport accessibility analyses, which aligns with SIREN's aim to evaluate service disruptions and prioritize infrastructure recovery efforts based on dynamic spatial accessibility metrics (Ford et al., 2015).

The concept of multimodal transport networks is central to SIREN's ambition of integrating humanitarian logistics, SAR operations, and civilian mobility. Smarzaro et al. advocate for the fusion of authoritative data and volunteered geographic information (VGI) to create responsive and inclusive transportation models (Smarzaro et al., 2021). During crises, platforms such as OpenStreetMap and Mapillary, combined with governmental road databases, can rapidly inform situational mobility modeling, offering a real-time view of road passability, congestion, and access to critical infrastructure.

Technological innovations, particularly in sensor integration and data fusion, are expanding the granularity of urban transport modeling. Ballouch et al. demonstrated how semantic segmentation of 3D point clouds from mobile LiDAR and UAVs can reveal pedestrian flow patterns, obstacle distribution, and transportation infrastructure conditions in unprecedented detail (Ballouch et al., 2024). In the SIREN framework, this enables semantic simulations that reflect the impact of debris, structural collapse, or flooding on transportation capacity and routing logic.

Despite these advancements, integrating transport modeling into holistic urban and emergency planning continues to face challenges. Rid and Zakharov et al. point to the persistent issues of data quality, institutional fragmentation, and limited interdisciplinary collaboration (Rid, 2017; Zakharov et al., 2018). Within SIREN, these concerns are addressed through semantic interoperability standards, stakeholder-centered co-design processes, and real-time simulation environments that bring together transportation planners, emergency responders, and municipal authorities.

By embedding transport infrastructure modeling into its semantic intelligence architecture, SIREN empowers cities to plan, simulate, and adapt multimodal transport systems not only for daily efficiency but also for critical continuity during disasters. This approach underscores the project's vision of a resilient urban mobility framework that is data-informed, dynamically coordinated, and responsive to both immediate emergencies and long-term recovery needs.

Use of UAV and Aerial Mobility Modelling

The integration of Unmanned Aerial Vehicles (UAVs) into aerial mobility modeling represents a transformative leap in disaster management, urban surveillance, and dynamic environmental assessment. Within the framework of the SIREN project, UAVs are pivotal for real-time spatial data acquisition, structural monitoring, and situational awareness in post-disaster environments, where ground-based access is often compromised.

UAVs offer a unique advantage in collecting high-resolution imagery and LiDAR data rapidly and efficiently, providing essential inputs for creating 3D digital twins of affected zones. This capability is particularly valuable in emergency scenarios requiring rapid damage assessment, route planning, and logistics optimization. For example, SIREN envisions the use of UAVs to map collapsed infrastructure, blocked roads, and the distribution of emergency shelters with centimeter-level accuracy.

Chen and Ding demonstrate the effectiveness of integrating UAV-derived data with Building Information Modeling (BIM) for linear infrastructure projects, an approach directly applicable to post-earthquake road assessment and reconstruction planning (Chen & Ding, 2024). In the SIREN context, this fusion supports the rapid re-evaluation of transportation networks, enabling the prioritization of restoration efforts.

The push toward sustainable aerial mobility has accelerated innovations in UAV charging and energy management systems. Al-Obaidi et al. highlight developments in energy-efficient charging pads for lightweight electric VTOL UAVs, a technology that could extend UAV endurance for continuous monitoring during prolonged emergencies (Al-Obaidi et al., 2020). These systems can be deployed at temporary logistics hubs in disaster zones to sustain UAV fleets supporting search-and-rescue (SAR), supply drops, or aerial surveillance.

Operational mobility modeling is also critical for effective UAV deployment in unpredictable and constrained urban airspaces. Sharma's mixed mobility model, simulating UAV coverage under urban conditions, aligns with SIREN's simulation platform by helping pre-define safe and optimal aerial corridors during disaster scenarios (Sharma, 2018). These models facilitate flight planning around no-fly zones, infrastructure hazards, or congested airspace occupied by manned emergency vehicles.

On the analytics front, the rise of semantic segmentation and AI-driven image processing has significantly improved the utility of UAV-captured data. Wei et al. introduced a Multi-View Stereo (MVS) method that converts 2D aerial imagery into semantically segmented 3D models, enabling responders to identify damaged buildings, flood zones, and open spaces suitable for temporary logistics bases (Wei et al., 2020). Such methodologies are directly applicable to SIREN's mission to establish a semantic understanding of disaster-hit urban topographies.

LiDAR integration into UAV platforms further enhances the accuracy of elevation models and change detection. As noted by Room and Anuar, these 3D datasets are critical for terrain modeling, landslide analysis, and watershed monitoring—key components of disaster risk mitigation (Room & Anuar, 2022). However, limited interoperability between LiDAR and mobile laser scanning (MLS) platforms remains a bottleneck. Bridging these gaps is essential for SIREN's goal of maintaining a unified, high-resolution geospatial intelligence system.

Indoor UAV navigation is another emerging domain relevant for disaster search operations in collapsed or confined structures. Kumar et al. present an integrated sensor framework capable of supporting autonomous indoor flight, highlighting the potential of UAVs to assist SAR missions in structurally compromised buildings (Kumar et al., 2017). This complements SIREN's ambition to expand UAV functionality beyond outdoor mapping.

Nonetheless, challenges persist in optimizing mission planning, especially under constraints of battery life, weather variability, and data bandwidth. Stache et al. underline the importance of mission-aware flight paths that adapt to both spatial requirements and UAV endurance limitations (Stache et al., 2022). Additionally, Meyer et al. stress the necessity of effective fusion between multimodal data—imagery, thermal data, inertial measurements, and semantic annotations—to support real-time decision-making (Meyer et al., 2019).

By integrating UAV systems into its semantic geospatial intelligence architecture, SIREN leverages the power of aerial mobility modeling not only to respond faster but also to build operational foresight through predictive simulation and AI-enhanced interpretation. This integration stands as a cornerstone of resilient, adaptive, and spatially intelligent disaster response ecosystems.

References:

Agugiaro, G. (2016). Enabling “energy-awareness” in the semantic 3d city model of vienna. ISPRS Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, III-4/W1, 81–88. https://doi.org/10.5194/isprs-annals-iii-4-w1-81-2016

Al-Obaidi, M., Mustafa, M., Hasan, W., Azis, N., Sabry, A., & Kadir, M. (2020). Improvement in energy conversion for unmanned aerial vehicle charging pad. Indonesian Journal of Electrical Engineering and Computer Science, 17(2), 767. https://doi.org/10.11591/ijeecs.v17.i2.pp767-773

Ballouch, Z., Hajji, R., Kharroubi, A., Poux, F., & Billen, R. (2024). Investigating prior-level fusion approaches for enriched semantic segmentation of urban lidar point clouds. Remote Sensing, 16(2), 329. https://doi.org/10.3390/rs16020329

Beil, C., Kendir, M., Ruhdorfer, R., & Kolbe, T. (2022). Dynamic and web-based 4d visualization of streetspace activities derived from traffic simulations and semantic 3d city models. ISPRS Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, X-4/W2-2022, 29–36. https://doi.org/10.5194/isprs-annals-x-4-w2-2022-29-2022

Biljecki, F., Kumar, K., & Nagel, C. (2018). CityGML application domain extension (ADE): Overview of developments. Open Geospatial Data, Software and Standards, 3(1). https://doi.org/10.1186/s40965-018-0055-6

Billen, R., Cutting-Decelle, A., Métral, C., Falquet, G., Zlatanova, S., & Marina, O. (2015). Challenges of semantic 3d city models. International Journal of 3-D Information Modeling, 4(2), 68–76. https://doi.org/10.4018/ij3dim.2015040106

Bimonte, S. (2016). Current approaches, challenges, and perspectives on spatial OLAP for agri-environmental analysis. International Journal of Agricultural and Environmental Information Systems, 7(4), 32–49. https://doi.org/10.4018/ijaeis.2016100103

Chaturvedi, K., & Kolbe, T. (2019). A requirement analysis on extending semantic 3d city models for supporting time-dependent properties. ISPRS Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, IV-4/W9, 19–26. https://doi.org/10.5194/isprs-annals-iv-4-w9-19-2019

Chen, L., & Ding, J. (2024). Application of BIM and UAV 3D reality modeling technology in highway engineering construction, 5. https://doi.org/10.1117/12.3054480

Fauzi, C. (2024). A review geospatial artificial intelligence (Geo-AI): Implementation of machine learning on urban planning. Jurnal Multidisiplin Indonesia, 3(1), 3752–3765. https://doi.org/10.58344/jmi.v3i1.1057

Ford, A., Barr, S., Dawson, R., & James, P. (2015). Transport accessibility analysis using GIS: Assessing sustainable transport in London. ISPRS International Journal of Geo-Information, 4(1), 124–149. https://doi.org/10.3390/ijgi4010124

Forget, Y., Linard, C., & Gilbert, M. (2018). Supervised classification of built-up areas in sub-Saharan African cities using Landsat imagery and OpenStreetMap. Remote Sensing, 10(7), 1145. https://doi.org/10.3390/rs10071145

Hao, M., Zhang, Y., Zhan, Q., Wang, D., Liu, Z., Liu, C., … & Fan, M. (2024). Research and application of urban 3D geologic modeling technology based on multivariate complex geologic structures—Take Chengdu as an example. https://doi.org/10.21203/rs.3.rs-4069685/v1

Jayaraj, P., & Ramiya, A. (2018). 3D CityGML building modelling from LiDAR point cloud data. The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences, XLII-5, 175–180. https://doi.org/10.5194/isprs-archives-xlii-5-175-2018

Jing, Y., Cui, J., Ma, D., & Chen, Y. (2023). Editorial: Towards sustainable urban development: Use of geographic big data for spatial planning. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1202661

Kumar, G., Patil, A., Patil, R., Park, S., & Chai, Y. (2017). A LiDAR and IMU integrated indoor navigation system for UAVs and its application in real-time pipeline classification. Sensors, 17(6), 1268. https://doi.org/10.3390/s17061268

Meyer, G., Charland, J., Hegde, D., Laddha, A., & Vallespi-Gonzalez, C. (2019). Sensor fusion for joint 3D object detection and semantic segmentation. https://doi.org/10.1109/cvprw.2019.00162

Parrado, N., & Donoso, Y. (2015). Congestion based mechanism for route discovery in a V2I-V2V system applying smart devices and IoT. Sensors, 15(4), 7768–7806. https://doi.org/10.3390/s150407768

Pfeffer, K., Martínez, J., O'Sullivan, D., & Scott, D. (2015). Geo-technologies for spatial knowledge: Challenges for inclusive and sustainable urban development, 147–173. https://doi.org/10.1007/978-3-319-21272-2_8

Prieto, I., Izkara, J., & Usobiaga, E. (2019). The application of LiDAR data for the solar potential analysis based on urban 3D model. Remote Sensing, 11(20), 2348. https://doi.org/10.3390/rs11202348

Rid, W. (2017). *Human dimensions approach towards integrating sustainable transportation and urban planning policies: A decision support system (DSS) based on stated preferences data*. Theoretical Economics Letters, 07(04), 814–833. https://doi.org/10.4236/tel.2017.74059

Room, M., & Anuar, A. (2022). *Integration of LiDAR system, mobile laser scanning (MLS) and unmanned aerial vehicle system for generation of 3D building model application: A review*. IOP Conference Series Earth and Environmental Science, 1064(1), 012042. https://doi.org/10.1088/1755-1315/1064/1/012042

See, L., Fritz, S., Perger, C., Schill, C., McCallum, I., Schepaschenko, D., … & Obersteiner, M. (2015). *Harnessing the power of volunteers, the internet and Google Earth to collect and validate global spatial information using Geo-Wiki*. Technological Forecasting and Social Change, 98, 324–335. https://doi.org/10.1016/j.techfore.2015.03.002

Sharma, P. (2018). *Coverage probability of 3D mobile UAV networks*. https://doi.org/10.48550/arxiv.1806.02937

Smarzaro, R., Davis, C., & Quintanilha, J. (2021). *Creation of a multimodal urban transportation network through spatial data integration from authoritative and crowdsourced data*. ISPRS International Journal of Geo-Information, 10(7), 470. https://doi.org/10.3390/ijgi10070470

Stache, F., Westheider, J., Magistri, F., Stachniss, C., & Popović, M. (2022). *Adaptive path planning for UAVs for multi-resolution semantic segmentation*. https://doi.org/10.48550/arxiv.2203.01642

Vanak, A., Panchamia, N., Banerji, I., & Nair, M. (2022). *A passive "OneHealth" surveillance system to track canine rabies in urban India*. https://doi.org/10.1101/2022.02.23.22271029

Vinasco-Alvarez, D., Samuel, J., Servigne, S., & Gesquière, G. (2021). *Towards limiting semantic data loss in 4D urban data semantic graph generation*. ISPRS Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, VIII-4/W2-2021, 37–44. https://doi.org/10.5194/isprs-annals-viii-4-w2-2021-37-2021

Wei, Z., Wang, Y., Yi, H., Chen, Y., & Wang, G. (2020). *Semantic 3D reconstruction with learning MVS and 2D segmentation of aerial images*. Applied Sciences, 10(4), 1275. https://doi.org/10.3390/app10041275

Xue, T., Hang, Z., & Shib, Y. (2024). *Enhancing efficiency in explicit 3D geological modeling and accuracy of attribute interpolation for urban underground spaces: A case study in Shanghai*. https://doi.org/10.21203/rs.3.rs-4010733/v1

Zahid, H., Hijazi, I., Donaubauer, A., & Kolbe, T. (2024). *Enhancing realism in urban simulations: A mapping framework for the German national standard XPlanung and CityGML*, 437–457. https://doi.org/10.1007/978-3-031-43699-4_28

Zakharov, D., Magaril, E., & Rada, E. (2018). *Sustainability of the urban transport system under changes in weather and road conditions affecting vehicle operation*. Sustainability, 10(6), 2052. https://doi.org/10.3390/su10062052

Zhang, X., Chen, C., Xu, Z., & Li, H. (2022). *Method and application of urban 3D rapid modeling of geology based on CAD borehole logs*. Geofluids, 2022, 1–12. https://doi.org/10.1155/2022/4959887

Zheng, Y., Weng, Q., & Zheng, Y. (2017). *A hybrid approach for three-dimensional building reconstruction in Indianapolis from LiDAR data*. Remote Sensing, 9(4), 310. https://doi.org/10.3390/rs9040310

Zhu, J., & Chowdhury, S. (2019). *Towards the ontology development for smart transportation infrastructure planning via topic modeling*. https://doi.org/10.22260/isarc2019/0068

Immersive Earthquake Simulation for Crisis Education in VR

Simulation Landscape and Educational Gaps

Traditional disaster simulation platforms—such as HAZUS (FEMA), OpenQuake (GEM Foundation), and CAPRA (World Bank)—serve expert audiences with quantitative risk assessment, loss estimation, and infrastructure fragility modeling. While powerful, these tools are not designed for public education or behavioral training. They fall short in preparing individuals for real-life emergencies due to:

- **Low User Engagement**: The user interfaces are largely 2D, data-centric tools with technical jargon and no embodied experience.
- **Lack of Interactivity**: Static models without support for real-time user decisions or their consequences. These tools do not simulate or respond to human decisions, thereby providing static, one-way learning
- **Limited Accessibility**: Technical barriers, high compute needs, and limited portability make them unsuitable for schools, municipal centers, or general audiences.

In contrast, VR-based simulations support first-person immersion, kinesthetic learning, and emotional imprinting—critical for crisis response. Recent academic studies such as Kinateder et al. (2014) and Lovreglio et al. (2018) confirm that immersive simulations significantly improve memory retention and situational awareness in disaster scenarios.

Our system addresses these gaps by transforming emergency response from a passive knowledge model to an active behavioral training experience. It equips users to internalize survival tactics through interactive simulation and real-time adaptation.

Real-Time Scenario Adaptation and Dynamic Outcomes

The evolution of real-time, interactive simulation has largely followed two trajectories: agent-based crowd simulation (e.g., EXODUS, Pathfinder) and procedural scenario engines (e.g., Unity-based emergency training modules). However, they often remain siloed from real-world datasets and operate with predefined behaviors.

Our system expands on this by integrating:

- **Procedural Content Generation**: Earthquake intensity, building fragility, NPC reactions, and secondary threats (e.g., fire, gas leaks) vary across sessions.
- **Decision-Tree AI**: NPCs and systems react to user actions—e.g., assisting NPCs can delay escape or trigger unexpected outcomes.
- **Replayability for Analysis**: Each session is unique, enhancing both training value and research usability.

Our implementation leverages Unity's runtime environment with integration of a flexible decision tree and procedural animation system that adapts to user input, environmental conditions, and stress parameters. By enabling on-the-fly scenario variations (e.g., changing earthquake strength, building resilience, NPC density), we create a sandboxed yet realistic environment.

Built using Unity and targeting Meta Quest and HTC Vive headsets, the simulation supports real-time feedback, low-latency interaction, and modular extensibility.

This approach aligns with emergent techniques in disaster training, such as:

- **Branching scenario engines** (used in medical and military simulation)
- **Multi-user VR fire drill simulations** (e.g., VR Fire Trainer by Bosch)
- **Real-time AI-driven disaster wargaming** (e.g., DARPA's GAMMA program)

Behavioral Design and Localized Realism

Human behavior in emergencies often deviates from textbook protocols. Disaster behavior is complex, culture-specific, and often counterintuitive. Most people freeze, delay evacuation, or act irrationally under duress.

Research from disaster sociology emphasizes the role of panic, groupthink, and cultural influence.

Our system incorporates human-centered design by integrating:

- **AI-Driven NPC Behavior**: Simulated crowd behavior (e.g., bottlenecks, panic waves) encourages players to adapt and anticipate human movement under stress.
- **Rich Environmental Cues**: Sounds of sirens, shaking furniture, dust clouds, and language-specific voice prompts engage sensory pathways.

Unlike static educational content, the simulation enables users to actively explore safe vs. unsafe decisions. Each action has consequences, contributing to a growing dataset on emergent disaster behaviors

Trust Through Transparency and Debriefing

A core barrier to adopting simulation-based education is skepticism toward accuracy and impact. We address this by embedding:

- **Behavioral Data Collection**: Every user session contributes to a growing behavioral dataset. This will form the foundation for future research into how people act during high-stress earthquake scenarios in VR.
- **Real-Time Debriefing System**: After each simulation, users receive personalized feedback visualizations, including:
  - Heatmaps of movements
  - A timeline of decisions
  - Key moments linked to outcomes (e.g., injury, escape success)
- **Explanation Agents**: A virtual guide summarizes user performance, linking behaviors to likely real-world consequences. For example, standing near windows during tremors may result in simulated injury.

These features are crucial in helping users trust the simulation as an accurate and beneficial training tool. They also provide a foundation for comparative studies on age, gender, prior knowledge, and reaction time under pressure.

In addition, we employ visual analytic dashboards that compare user choices to optimal paths, similar to the training analytics used in firefighter VR modules or pilot training.

New Frontiers in Human Behavior Research

Unlike traditional simulations that replicate known hazards, our system pioneers a new avenue: studying human reactions under controlled but varied disaster conditions. Key contributions include:

- **Empirical Data for Behavior Modeling**: By collecting movement, gaze, and interaction patterns, we can identify behavioral archetypes (e.g., risk-takers vs. cautious actors).
- **Human-in-the-Loop Analytics**: Researchers can replay, tag, and compare behaviors, forming the basis for new psychological or urban planning insights.
- **Cross-Demographic Impact**: Simulations can be customized to explore how age, culture, and prior training influence performance.

This turns the VR system into both a training platform and a behavioral research laboratory.

Our VR earthquake simulator serves dual roles: as an immersive education tool and as a novel behavioral research environment. It moves beyond traditional scenario modeling to a responsive, emotionally engaging, and culturally relevant educational tool. Developed in Unity for widely available VR devices, it is scalable, modular, and culturally adaptable. Unlike analytical-only tools, it empowers users to practice and refine survival behavior—then learn from their experience.

As part of the SIREN project, this system strengthens preparedness across schools, public institutions, and research communities. By transforming disaster training into an embodied, data-generating, and emotionally resonant experience, we redefine the role of simulation in public safety.

References

- FEMA HAZUS: https://www.fema.gov/flood-maps/products-tools/hazus
- GEM OpenQuake: https://www.globalquakemodel.org/product/openquake-engine
- World Bank CAPRA: https://ecapra.org
- EXODUS by University of Greenwich: https://fseg.gre.ac.uk/exodus
- Pathfinder by Thunderhead Engineering: https://www.thunderheadeng.com/pathfinder
- VR Fire Trainer by Meta: https://www.meta.com/experiences/vr-fire-trainer/5720757854645619
- Kinateder et al. (2014): https://arxiv.org/pdf/1805.09138
- Lovreglio et al. (2018): https://files.thunderheadeng.com/femtc/2020_d3-02-lovreglio-paper.pdf
- Kolb's Experiential Learning Theory: https://www.verywellmind.com/experiential-learning-2795154

Communication Network

3GPP standards for emergency and disaster-resilient communication networks: SoA, limitations, challenges

3GPP has long acknowledged the importance of ensuring communication resilience in emergency and disaster scenarios. From the early days of public safety communications in LTE (e.g., Proximity Services – ProSe and Mission-Critical Push-to-Talk – MCPTT) to the evolving features of 5G networks, there has been continuous standardization effort to ensure service continuity, reliability, and responsiveness during disasters. These efforts are critical in enabling emergency alerts, public warning systems, coordination among first responders, and communication restoration in damaged or overloaded networks.

There are five 3GPP technologies and solutions supporting disaster scenarios: 1) Access Traffic Steering, Switching, and Splitting (ATSSS); 2) Terrestrial and Non-Terrestrial Network (TN/NTN) Integration; 3) Mission-Critical Services; 4) Cellular Vehicle-to-Everything (C-V2X) and D2D Communication; 5) Public Warning System (PWS) and Cell Broadcast Services.

Let's briefly consider the current standardization status of each mechanism and existing limitations.

1) Access Traffic Steering, Switching, and Splitting (ATSSS)

The ATSSS framework[50] has been standardized since 3GPP Release 16 and provides multi-access support by allowing devices to utilize simultaneous connections over both 3GPP (e.g., 5G NR) and non-3GPP (e.g., Wi-Fi) interfaces.

This 3GPP feature enables seamless traffic steering and switching based on real-time link conditions; load balancing and redundancy, which are essential in disaster scenarios; improved service availability when one access technology (e.g., mobile base stations) is degraded, e.g. due to disaster damages.

Limitation: while ATSSS increases robustness, its implementation is limited by centralized control and static policies, making it less responsive to rapidly changing disaster contexts.

2) Terrestrial and Non-Terrestrial Network (TN/NTN) Integration

3GPP has been actively developing technical specifications to integrate Non-Terrestrial Networks (NTNs) such as LEO satellite systems into the 5G system architecture, i.e. Terrestrial Networks (TNs) since Release 16[51].

This integrational solution is crucial for ensuring connectivity in remote, rural, or damaged areas where terrestrial networks are unavailable; supporting broadcast alerts and emergency communications in real time; enabling backhaul redundancy and survivability through satellite links.

Limitation: this hybrid TN/NTN solution is particularly valuable in disaster response but faces challenges such as high latency and link variability in NTN and limited integration with on-the-ground adaptive mechanisms.

3) Mission-Critical Services

Through technical specifications like MCPTT[52], MCVideo[53], and MCData[54], 3GPP has provided a framework for mission-critical communication services that are applicable for public safety agencies; first responders; command and control centres.

This 3GPP solution includes group calls with high reliability and low latency; priority and pre-emption mechanisms; secure authentication and communication.

Limitation: although Mission-Critical Services ensure guaranteed communication quality and priority in emergencies, they are strongly related to pre-defined QoS frameworks, static resource allocations, and operator provisioning. These are factors that can become bottlenecks in rapidly evolving, unstructured disaster environments.

4) Cellular Vehicle-to-Everything (C-V2X) and device-to-device (D2D) Communication

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50 3GPP TS 24.193, Access Traffic Steering, Switching and Splitting (ATSSS)
51 3GPP TR 38.821, Solutions for NR to support non-terrestrial networks (NTN)
52 3GPP TS 23.379, Mission Critical Push to Talk (MCPTT) architecture and functions
53 3GPP TS 23.281, Functional architecture and information flows to support Mission Critical Video (MCVideo)
54 3GPP TS 23.282, Functional architecture and information flows to support Mission Critical Data (MCData)

C-V2X and D2D communication mechanisms (e.g., ProSe[55]) allow for local communication even when infrastructure is damaged.

In particular, these mechanisms support peer-to-peer data exchange; mesh-like connectivity in edge scenarios; low-latency coordination for rescue operations.

Limitation: while promising, C-V2X and D2D technologies remain underutilized due to security, trust, and interference management issues and lack of implementation of dynamic coordination and AI-driven situational awareness features.

5) Public Warning System (PWS) and Cell Broadcast Services

3GPP includes support for Public Warning Systems (PWS)[56] via Cell Broadcast (CBS)[57] and Earthquake and Tsunami Warning Systems (ETWS).

These features enable dissemination of time-critical alerts to large populations and area-specific messaging without network congestion.

Limitation: these systems and services are unidirectional, rule-based, and lack personalization or intelligent context adaptation, which limits their effectiveness during complex disaster scenarios.

While the above five 3GPP technologies and solutions supporting disaster scenarios offer crucial tools for improving network resilience, several key limitations still persist.

[55] 3GPP TS 23.303, Proximity-based Services (ProSe) Architecture aspects
[56] 3GPP TS 22.268: Public Warning System (PWS) requirements
[57] 3GPP TS 23.041: Technical realization of Cell Broadcast Service (CBS)

Gaps and challenges in current 3GPP framework are summarized in the following table:

Challenge/gap	**Description**
Static and rigid architectures	Most current systems rely on centralized decision-making, static configuration, and predefined policies, limiting responsiveness and adaptability.
Lack of real-time autonomy	The absence of intelligent, distributed agents hinders autonomous response, resource reallocation, or topology reconfiguration in dynamic disaster settings.
Insufficient context awareness	Disaster scenarios require real-time adaptation to localized conditions. Current systems are not natively context-aware or goal-driven.
Fragmented interoperability	While ATSSS and TN/NTN help, multi-access coordination, trust management, and workload orchestration remain complex and inflexible.
Limited use of AI	Emerging AI is not yet seamlessly integrated into 3GPP protocols in a way that allows explainable, adaptive, and collaborative decision-making.

The limitations mentioned in the table underscore the need for a next-generation architectural evolution. This evolution requires **agentic AI-based intelligent communication** that goes beyond static current network capabilities and can be considered as a tool to address challenges in current 3GPP networks for disaster scenarios. This would allow communication networks to:

- Deploy autonomous AI agents with reasoning, collaboration, and planning abilities;
- Support real-time decision-making and adaptation in volatile disaster contexts;
- Provide self-organizing and self-healing capabilities across all nodes and layers.

Such an architectural evolution will be explored in the subsequent sections and deliverables of the SIREN project, where we define agentic AI-driven communication opportunities and solutions to address different use cases related to disaster scenarios.

Ongoing 3GPP 6G work relevant to disaster scenarios, gaps, and agentic AI-driven communication opportunities

The 3GPP TR 22.870[58] of SA1 group (Release 20) identifies key use cases and service requirements for 6G networks. Among these, several use cases are directly relevant to disaster resilience and emergency communications. Examples of these use cases are:

- Resilient Positioning and Emergency Services that emphasizes the need for systems that can function independently of Global Navigation Satellite System (GNSS) during interruptions, ensuring high accuracy and availability of location data in both terrestrial and non-terrestrial frameworks. This is crucial for maintaining communication continuity during crises, supported by portable mini-networks and satellite capabilities.
- Intelligent unmanned aerial vehicles (UAVs) swarms propose the use of UAVs equipped with AI agents to capture real-time images and execute tasks for disaster monitoring, surveillance, and object detection. Such swarms can provide rapid situational awareness and assist in search and rescue operations.
- Collaborative AI Agents use case considers autonomous AI agents operating in various domains, including connected cars and smart cities, leveraging edge/cloud computing for real-time decision-making. In disaster scenarios, these agents can facilitate dynamic network reconfiguration and resource allocation to maintain service continuity.

These use cases underscore the necessity for networks that are not only robust and resilient, but also intelligent and adaptive. The integration of agentic AI, or in other words, AI systems capable of autonomous decision-making and collaboration into mobile network architectures can address the complexities of disaster scenarios. In particular, it can enable:

- Autonomous network reconfiguration by means of AI agents can dynamically adjust network parameters and configurations in response to changing conditions, ensuring optimal performance even when parts of the network are compromised or damaged.
- Real-Time decision making by means of AI agents in rapidly evolving disaster situations can be based on analyzing vast amounts of data in real-time to make informed decisions, such as re-routing traffic or prioritizing emergency communications.
- Enhanced situational awareness through the deployment of intelligent UAV swarms and other sensing devices where AI agents can gather and process environmental data, providing a comprehensive understanding of the disaster landscape.
- Seamless integration of heterogeneous networks where Agentic AI can facilitate the coordination between terrestrial and non-terrestrial networks, ensuring uninterrupted connectivity even when traditional infrastructure is damaged.

Incorporating these capabilities into future mobile network communication will be the key point in enhancing disaster preparedness and response, aligning with the objectives outlined in 3GPP TR 22.870.

Note that the analysis provided in this section is based on the current draft versions of 3GPP TR 22.870 V0.2.1 and related documents. As the standardization process is ongoing, further updates and refinements to these use cases and requirements are expected.

We have analysed 3GPP TR 22.870 V0.2.1 and selected 7 use cases that are relevant to disaster scenarios and 3 use cases related to Autonomous Mobile Robots (AMRs) that also can be involved in disaster scenarios. In the next two subsections we analyse these use cases from the viewpoint of their relevance to disaster scenarios, gaps in the current communication systems to support these use cases and agentic AI opportunities to address these gaps.

[58] 3GPP TR 22.870 V0.2.1, Study on 6G Use Cases and Service Requirements

Analysis of 3GPP 6G use cases about disaster scenarios

In this subsection we consider the following 6G use cases from 3GPP TR 22.870 V0.2.1 that we believe can be relevant to disaster scenarios:

5.4.2 Fast network provisioning to improve resilience;
6.13 Use case on Intelligent UAV Swarms;
7.1 Use Case on coordination of search and rescue missions in large disaster areas;
7.10 Use case on historical sensing data transfer;
8.1 Use case on Ubiquitous and Resilient Network;
8.5 Use case on "Disaster relief";
10.1 Use Case on wide-area coverage.

Below we describe shortly each use case, its disaster scenario relevance, current gaps, and agentic AI opportunities.

5.4.2 Fast Network Provisioning to Improve Resilience

Short description. This use case considers the need for rapidly deployable and reconfigurable networks *after a disruption* (e.g., earthquake, flood, infrastructure collapse).

Relevance. In large-scale disasters, fixed infrastructure is often damaged. Fast network provisioning using edge units, drones, or portable base stations becomes essential.

Gap. Current systems require manual reconfiguration and lack autonomy in deployment and self-optimization.

Agentic AI Opportunity. Agent-based systems can autonomously deploy and orchestrate edge infrastructure, predict coverage gaps, and self-organize based on the context and mission priority.

6.13 – Use Case on Intelligent UAV Swarms

Short description. Unmanned Aerial Vehicles (UAVs) can be used to enhance coverage, relay communications, and conduct monitoring and assessment tasks in disaster areas.

Relevance. Coordinated UAV swarms can act as temporary networks when ground-based infrastructure is unavailable.

Gap. Lack of intelligent coordination, adaptive decision-making, and real-time collaboration among drones.

Agentic AI Opportunity. Networked AI agents embedded in UAVs can support distributed coordination, adaptive flight path planning, and collaborative sensing/communication in disaster zones.

7.1 Coordination of Search and Rescue Missions in Large Disaster Areas

Short description. Coordination of different entities (e.g., UAVs, robots, humans) involved in Search and Rescue (SAR) operations using real-time, context-aware communication.

Relevance. Multi-agent collaboration with autonomous capabilities is key in SAR operations.

Gap. Current networks do not support context-aware dynamic mission coordination between heterogeneous agents.

Agentic AI Opportunity. Agentic AI can enable decentralized task allocation, dynamic mission adjustment, and real-time information sharing between all participating entities.

7.10 Use Case on Historical Sensing Data Transfer

Short description. The use case deals with capturing and transferring large amounts of environmental and sensor data from remote locations for analysis and decision-making.

Relevance. It is critical for post-disaster assessments, early warning systems, or forensic investigations.

Gap. There are delays or limitations in data transfer due to lack of adaptive routing and prioritization mechanisms.

Agentic AI Opportunity. AI agents can intelligently manage data offloading, prioritization, and compression based on urgency, relevance, and network availability.

8.1 Use Case on Ubiquitous and Resilient Network

Short description. The use case ensures communication coverage is maintained under all conditions — urban, rural, remote, and disaster-struck areas.

Relevance. This is the central framework for any resilient emergency communication system.

Gap. Current systems lack real-time adaptability and self-healing capabilities in highly dynamic conditions.

Agentic AI Opportunity. AI-native agents enable on-the-fly reconfiguration, predictive fault handling, and autonomous coverage recovery.

8.5 Use Case on Disaster Relief

Short description. This use case focuses directly on communication support during emergency response including coordination, data sharing, and situational awareness.

Relevance. This is a foundational use case for SIREN motivation and objectives.

Gap. Fragmented solutions today depend heavily on manual setup and fail to adapt in real-time to changing environments.

Agentic AI Opportunity. Decentralized AI agents can support autonomous decision-making, contextual prioritization, and collaborative coordination across first responders, command centres, and field devices.

10.1 – Use Case on Wide-Area Coverage

Short description. This use case covers a need for mobile or satellite-assisted wide-area coverage, especially in underdeveloped or affected regions.

Relevance. This is a key factor in disaster situations where infrastructure is damaged or inaccessible.

Gap. Lack of AI-native mechanisms to manage satellite-terrestrial integration, handover, and data distribution.

Agentic AI Opportunity. Agent-based AI systems can optimize the balance between terrestrial and non-terrestrial connectivity based on dynamic context and mission needs.

Analysis of use cases about AMRs that can be involved in disaster scenarios

In this subsection we consider the following 6G use cases from 3GPP TR 22.870 V0.2.1 about AMRs that can be involved in disaster scenarios:

7.7 Supporting Intelligence Leveraging Nearby Entities for Real-Time Awareness;

11.2 Use Case on Cooperating Mobile Robots;

11.8 Use Case on Collaborative Awareness in Dynamic Environments - Enhancing Mutual Decision-Making through Real-Time Data Sharing.

Below we describe shortly each AMR-related use case, its disaster scenario relevance, current gaps, and agentic AI opportunities.

7.7 Supporting Intelligence Leveraging Nearby Entities for Real-Time Awareness

Short description. This use case explores how AMRs can improve operational performance by using environmental awareness from nearby devices (e.g., sensors, drones, cameras, vehicles). The robots adapt based on this shared contextual information. In particular, AMRs utilize intelligence from nearby entities (e.g., sensors, cameras, other robots) to enhance situational awareness.

Relevance. In disaster scenarios, AMRs deployed for search, rescue, or logistics benefit greatly from external real-time awareness when direct sensing is limited (e.g., blocked line-of-sight, dust, darkness). In post-disaster environments where visibility and access are limited, AMRs benefit from externally sourced context to avoid obstacles, detect survivors, or map hazards.

Gap. Current networks lack real-time intelligence-sharing frameworks that are distributed, scalable, and adaptable to rapidly changing environments or ad hoc deployments. In particular, 5G and legacy networks lack intelligent, real-time, peer-to-peer coordination mechanisms that allow AMRs to adapt their behaviour based on dynamic, distributed data.

Agentic AI Opportunity. AI agents embedded in AMRs and environmental nodes can autonomously share, filter, and prioritize awareness data using local context and mission goals, enabling more intelligent and decentralized decision-making.

11.2 Use Case on Cooperating Mobile Robots

Short description. The use case focuses on multi-AMR collaboration in logistics, inspection, and navigation, requiring synchronization, route planning, and load balancing among the mobile agents.

Relevance. In disaster scenarios, AMRs must coordinate to efficiently search debris, transport supplies, map damage zones, or support rescue operations. In particular, during emergency logistics or rescue operations, coordinated AMRs can divide search areas, transport medical supplies, or collectively clear debris.

Gap. There's a lack of adaptive, network-native cooperation protocols to support task orchestration and reliable real-time communication between mobile robots, especially in disrupted or resource-constrained networks.

Agentic AI Opportunity. Agentic AI-based network enables robots to act as network-aware agents completing negotiating tasks, adjusting to connectivity disruptions, and adapting plans in real time based on mission status, resource availability, and local observations. In particular, AI agentic network allows AMRs to serve as autonomous and mission-coordinated agents. Through local negotiation, AI agents dynamically allocate tasks based on capabilities, location, and connectivity to ensure continuity of operations even under partial network failure.

11.8 Use Case on Collaborative Awareness in Dynamic Environments – Enhancing Mutual Decision-Making through Real-Time Data Sharing

Short description. In this use case AMRs and other intelligent entities share real-time data and collaborate in fast-changing environments to improve mutual decision-making and safety.

Relevance. Highly applicable in unpredictable disaster conditions, where rapid, decentralized responses are essential and central coordination is often unavailable or slow. Shared awareness is critical in hazardous zones where robot paths, threats, and priorities change constantly.

Gap. The current network paradigm lacks the autonomy and intelligence needed to support mutual context understanding and distributed learning in real time.

Agentic AI Opportunity. Embedded AI agents in both the network infrastructure and AMRs allows autonomous adaptation to shifting operational conditions and ensuring mission-aligned data sharing, decentralized planning, and cooperative behaviour. In particular, they enable mutual goal alignment and real-time context interpretation, allowing entities to reason jointly about their environment, respond to unanticipated conditions, and act in coordinated autonomous ways.

Thus, key potential benefits that Agentic AI can bring to disaster response if AMRs are involved in the disaster area are:

- Decentralized Intelligence and autonomy, i.e. agentic AI allows robots to operate even with intermittent connectivity, maintaining local decision-making. AI agents embedded in AMRs and network functions operate independently with reduced reliance on a central controller.
- Mission-aware networks and adaptivity, i.e. the network itself adapts to AMR behaviour and mission urgency, e.g., prioritizing uplink for hazard detection. That is, mission-driven decision-making enables evolving based on goals, urgency, and changing constraints.
- Dynamic task allocation and intelligence, i.e. AI agents negotiate workload based on robot location, battery, or data quality. Embedded AI agents within the network dynamically adjust bandwidth, prioritize critical AMR communication, and manage congestion or link failures intelligently.
- Situational flexibility that enables robots to reroute or adjust tasks on the fly without manual input.
- Multi-Agent Collaboration that enables heterogeneous agents (e.g., ground robots, UAVs, sensors) to share intent, learn collectively, and coordinate plans effectively.

Thus, the integration of agentic AI into mobile networks offers a paradigm shift from mere connectivity to mission-aware, distributed intelligence. In disaster scenarios, this ensures resilient, adaptive, and collaborative communication environments which are essential for next-generation autonomous operations.

New Use Case on multi-MNO cooperative service continuity in disaster scenarios

Use case description. In large-scale disasters (e.g., earthquakes, floods, wildfires), Mobile Network Operators (MNOs) may experience infrastructure outages in the affected areas. Subscribers of an MNO whose network is down (MNO-A) are typically left without connectivity, even if neighbouring infrastructure owned by other MNOs (e.g., MNO-B) remains operational. This use case describes a scenario where MNO-B temporarily hosts subscribers of MNO-A via inter-PLMN (Public Land Mobile Network) network sharing, including dynamic network slicing and roaming-based service continuity mechanisms. The system would autonomously assess the situation, negotiate policies between operators, and provision secure, limited-access connectivity for critical and emergency services (e.g., emergency calls, alerts, rescue coordination).

Relevance to Disaster Recovery. This use case is critical for enhancing communication resilience. Ensuring basic connectivity (e.g., emergency calls, alerts, and location tracking) can save lives during the initial hours following a disaster. It also ensures communication among first responders, civil protection teams, and autonomous systems (like AMRs or UAVs) that rely on mobile infrastructure. While national roaming agreements exist in some countries, current deployments are static, manually controlled, and not optimized for rapid autonomous disaster response.

Gap. Although 3GPP TR 22.870 V0.2.1 includes Use Case 5.4.2 ("Fast network provisioning to improve resilience"), the focus is intra-operator, addressing local restoration through UAVs, nomadic cells, or transportable network components. The concept of cross-MNO collaboration for real-time service continuity via dynamic inter-PLMN roaming, network slicing, or temporary subscriber redirection is not explicitly covered. There are no defined mechanisms in current standards for real-time negotiation of QoS, security policies, or slice orchestration between MNOs in emergency contexts[59][60][61].

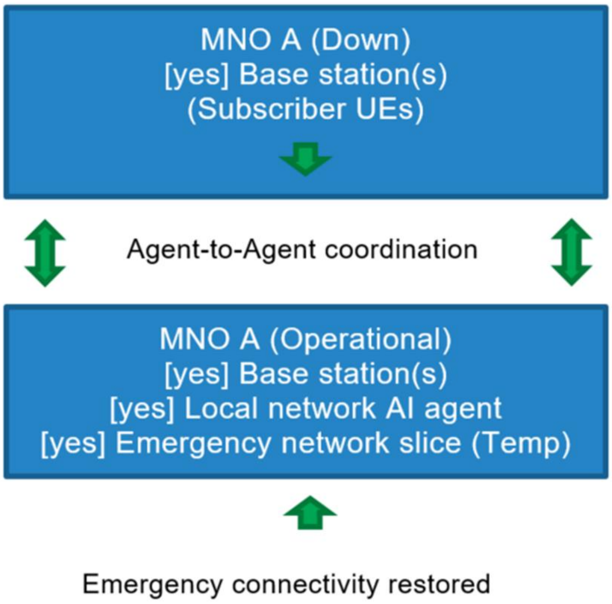
Agentic AI Opportunity. Agentic AI-based network introduces autonomous AI agents capable of real-time negotiation, decision-making, and inter-operator coordination. In this use case:

- MNO-A's agent detects infrastructure failure and signals for disaster-mode fallback.

[59] 3GPP TS 23.501, System architecture for the 5G System (5GS)
[60] 3GPP TS 23.502, Procedures for the 5G System (5GS)
[61] 3GPP TR 28.808, Study on inter-PLMN network slicing management architecture

- MNO-B's agent receives the request, evaluates current network load and policies, and dynamically allocates resources (e.g., creates a slice or prioritizes bandwidth).
- Both agents coordinate securely and automatically using predefined or AI-learned policies, leveraging protocols like IETF ALTO ("Application-Layer Traffic Optimization" for inter-domain decisions) and 3GPP inter-PLMN interfaces.

This scenario for agentic AI communication is illustrated in Figure below:



The coordination between the two MNOs is performed autonomously by intelligent network agents embedded within an AI-native agentic architecture. These agents are capable of assessing the situation, exchanging information securely, and negotiating temporary network resource sharing agreements (e.g. network slicing, emergency roaming) in real-time.

This enables MNO-A's subscribers to connect through MNO-B's infrastructure without prior static agreements or manual intervention, improving the resilience of mobile networks and enabling rapid response to emergencies.

This way, the AI agents ensure trustworthy, explainable, and context-aware resource allocation and user admission, minimizing manual intervention. This also supports service continuity for autonomous systems (e.g., AMRs, UAVs) involved in rescue operations, which may rely on real-time low-latency connectivity.

Agentic AI-based communications as a tool to address challenges in traditional networks for disaster scenarios

The analysis of current 3GPP standards and ongoing 6G use case study made in the previous sections clearly reveals that existing traditional mobile networks, while increasingly advanced, still face critical limitations in disaster scenarios. These limitations include rigid infrastructure, centralized decision-making, insufficient interoperability between operators, and lack of real-time adaptability to dynamic and large-scale emergency environments.

Disaster scenarios demand communication systems that are autonomous, context-aware, and capable of operating under partial infrastructure availability or complete outages. Current 3GPP approaches (such as ATSSS, TN/NTN integration, and mission-critical services) provide foundational tools but lack holistic coordination and self-adaptive intelligence across layers and domains.

Agentic AI-based mobile network communications introduce a new paradigm by embedding distributed, intelligent agents throughout the network from UEs and RAN nodes to the core network and edge/cloud computing platforms. These AI agents are designed to observe, think, learn from their environment, and take autonomous actions and decisions based on goals and context. In disaster scenarios, such capabilities can fundamentally change how networks behave and recover.

Key benefits of agentic AI-based communications in disaster response scenarios include:

- Autonomous resilience and reconfiguration, i.e. AI agents can detect infrastructure failure, isolate affected zones, and initiate self-healing or alternative routing paths without requiring manual coordination.
- Cross-operator service continuity, i.e. AI agents can negotiate temporary resource and slice sharing between MNOs, enabling subscribers of a failed network to access critical services via neighbouring networks.
- Collaboration with Intelligent devices, i.e. embodied AI agents in AMRs, UAVs, and sensors can coordinate with network AI agents to share real-time situational data, adjust communication parameters, and co-manage connectivity.
- Dynamic prioritization and resource optimization, i.e. AI-agents can dynamically assess mission-criticality, allocate spectrum, bandwidth, and compute resources based on evolving needs.

By integrating these capabilities, agentic AI-based networking can become not just a reliable communication tool, but an active contributor to emergency response operations. This agentic AI feature enables the network communications to become proactive, intelligent, and resilient, transforming disaster recovery timelines and operational effectiveness.

As 6G continues to evolve within the 3GPP activity and other standardization bodies, embedding agentic AI intelligence into the network architecture will be essential to meet the requirements of next-generation critical services, including public safety, autonomous systems, and resilient IoT ecosystems.

Telecommunications Methods for Locating Individuals in Disaster Situations

Locating individuals after disasters is crucial for effective emergency response. Telecommunications (telco) technologies play a pivotal role in this process by leveraging mobile networks, data analytics, and innovative communication methods.

Mobile Phone Location Data

Call Detail Records (CDRs): Analyzing anonymized CDRs can help track population movements and identify displaced individuals. This method has been used to assess internal displacements following sudden-onset disasters. ([1908.02377] Detecting individual internal displacements following a sudden-onset disaster using time series analysis of call detail records)

Emergency Calling Services (i.e. 112 and 911)

Enhanced 911 (E911) in North America and Advanced Mobile Location (AML) in Europe are two critical systems designed to automatically transmit a caller's location to emergency services when dialing 911 or 112, respectively. These systems rely on either the telecommunications network or the smartphone itself to deliver accurate geolocation data, facilitating faster and more effective emergency responses. However, both methods are activated only during an active emergency call.

They do not function if the individual does not place a call or is unable to place a call, such as in cases where post-disaster infrastructure is severely disrupted or mobile networks are down. These methods also require minimum specific versions of mobile phone software.

Enhanced 911 (E911): In North America, E911 provides dispatchers with the caller's location information, improving the efficiency of emergency services. (https://www.fcc.gov/general/enhanced-9-1-1-wireless-services) this service is being further enhanced to and being labeled as "Next Generation 911" (abbreviated NG911) (Next Generation 911 | 911.gov). AML was standardised by the European Telecommunications Standards Institute (ETSI) Emergency Telecommunications Subcommittee (EMTEL) in 2019 as Technical Specifications https://www.etsi.org/deliver/etsi_ts/103600_103699/103625/01.01.01_60/ts_103625v010101p.pdf. Next Generation 112 is also defined in this same specification.

Mobile Network-Based Population Mapping

Telecommunications providers can use anonymized mobile phone data to map population densities and movement trends. This allows emergency planners to identify high-risk zones with dense populations and anticipate evacuation needs. During a disaster, these insights support dynamic resource allocation and shelter planning based on real-time human mobility patterns. Although useful for planning, this method is not suitable post disaster since it is anonymized.

https://arxiv.org/abs/2108.02849?utm_source=chatgpt.com

Predictive Analytics on Movement Data

By examining historical and real-time mobile data, researchers and disaster managers can predict how people are likely to move in response to hazards like earthquakes or floods. This allows for optimized evacuation route planning and proactive traffic control to reduce congestion during mass movements.

https://arxiv.org/abs/1811.03598?utm_source=chatgpt.com

Network Optimization After Disasters

Key Academic and Industry Resources on SON (Self Organized Networks) in Disaster Scenarios

1. "Self-Organizing Networks for 5G and Beyond: A View from the Top"

This comprehensive review discusses SON architectures and their evolution, highlighting European research initiatives like SOCRATES, SEMAFOUR, SESAME, COGNET, and BeFEMTO. It emphasizes SON's role in enhancing network resilience and efficiency in 5G and future networks.
https://www.mdpi.com/1999-5903/14/3/95

2. "Self-Organization in Disaster Resilient Heterogeneous Small Cell Networks"

This study explores self-configuration and self-optimization techniques in heterogeneous small cell networks, demonstrating their effectiveness in improving network performance during disasters.
https://arxiv.org/abs/1505.03209

3. "Enabling Disaster Resilient 4G Mobile Communication Networks"

The paper introduces a Flexible Management Entity (FME) to enhance 4G LTE network resilience, allowing for continued communication even when parts of the network are compromised.
https://arxiv.org/abs/1406.0928

4. "Fast Network Recovery from Large-Scale Disasters: A Resilient and Self-Organizing RAN Framework"

Focusing on the 2023 earthquakes in Turkey, this research presents a framework for rapid network recovery using AI-based RAN controllers and integration of terrestrial and non-terrestrial nodes.
https://arxiv.org/abs/2408.08609

5. Innovile's Case Study on SON Solutions in Natural Disasters

This industry case study details how SON solutions were applied during natural disasters in Turkey to maintain network connectivity and manage traffic dynamically, prioritizing emergency communications.
https://www.innovile.com/resources/insights/harnessing-son-solution-in-natural-disasters-how-self-organizing-networks-and-mobile-network-automation-can-reinforce-resilience-turkey-case-study/

Wearable Tech for Emergency Responders

Wearable and sensor technologies have driven important progress in monitoring first responders, particularly firefighters, by tracking physiological and cognitive load, environmental exposures, location, and safety features like man-down detection. Recent research has further deepened the understanding of how these technologies can specifically support firefighters by continuously monitoring physical activity, health indicators, and core body temperature during operations.

Given the high risks firefighters face, including sudden cardiac death and cardiovascular diseases during emergency duties, monitoring vital signs such as heart rate is crucial, as elevated levels can impair performance. Furthermore, exposure to hazardous substances like carbon monoxide presents serious health dangers, including loss of consciousness and impaired oxygen transport in the blood. Prolonged or acute exposure can lead to neurological symptoms such as depression, confusion, and memory loss, while acute toxicity can damage the nervous system and heart, potentially resulting in death, underscoring the importance of integrating environmental sensors alongside physiological monitoring.

The use of sensors integrated into Personal Protective Equipment (PPE) is increasing and represents an effective way to enhance protection, reduce risks and prevent accidents and occupational diseases. Smart PPE enables real-time monitoring through embedded sensors, providing information that can be used to send alerts, track specific location data, monitor health indicators, and improve communication during emergency response (Weidinger et al., 2022).

Sensors for real-time monitoring of critical physiological signals, such as heart rate (HR), respiratory rate (RR), skin temperature (Tsk), have been integrated into fire-resistant shirts or wearable sensor vests used by firefighters. Findings from previous studies demonstrate their potential for early detection of heat stress or physical workload conditions without compromising mobility or comfort. Results are promising about the accuracy under extreme heat conditions and the influence of the firefighter's protective outerwear on signal acquisition. However, it remains essential to evaluate different sensor technologies, not only in controlled laboratory conditions, but also in real-emergency scenarios.

Some of these smart solutions are already commercially available. For instance, the ARMOR - Heat Stress Monitoring Wearable by EVALAN IoT, provides real-time biometric data to help professionals to detect early signs of heat stress. The Hexoskin Smart Shirts - Cardiac, Respiratory, Sleep & Activity Metrics, continuously monitor metrics such as sleep quality and HRV, supporting the assessment of mental health and stress, operational stress injuries, and post-traumatic stress disorder among first responders.

Other smart wearable solutions, such as fall detection systems, enable the identification of firefighter falls by integrating motion sensors into various parts of the body or into personal protective clothing.

However, wearable sensors, whether worn directly on the body or embedded in garments, also present challenges, including ensuring long-term durability, comfort under layered protective clothing, wearable charging under dynamic conditions, and reliable data transmission in high-risk and high-temperature environments. Additionally, some PPE may not always be used by professionals or could be more susceptible to damage. In view of this, the integration of sensors (e.g. location and motion) on professional boots can contribute to solve these problems. Foot plantar pressure distributions data, captured from wearable insole pressure sensors, has been used to detect and classify loss of balance events. Additionally, balance data can be used beyond predicting the risk of falls, as changes in stability can result from muscle fatigue or pain. Furthermore, other sensors can be integrated in boots and also used, such as location sensors. Along with other wearables (e.g. chest band wearable), this can provide important information about the subject’s physical and mental condition. Such information, coupled with other data regarding subjects’ skills and location, can facilitate swift responses and contribute to human resources management in a crisis.

Even though smart wearable technologies for firefighters are advancing, several issues still need to be addressed. One of them is interoperability. It is important that sensors and systems communicate well with each other, allowing to integrate them into unified platforms during emergency operations. Another important aspect is data privacy and security, especially when personal health and location data are involved. Finally, despite the promising results of some solutions, there is still a lack of validation under real operational scenarios. Some systems have not been tested extensively outside of the lab, so we still do not know how reliable or effective they really are under real disaster scenarios.

Local Data Processing and Bandwidth Optimization

Recent advancements in wearable sensor technologies have enabled the seamless integration of pressure sensors in boots, ECG chest bands, and EEG caps into the protective clothing of first

responders. This development introduces new challenges related to data transmission, real-time feedback, and operational efficiency, particularly in the high-pressure environments characteristic of emergency response.
This local data processing paradigm, also referred to as edge computing, enables the system to extract meaningful features such as heart rate variability, gait asymmetries, or cognitive fatigue markers directly on the device. As a result, real-time decision-making support can be provided to first responders through on-body multimodal feedback mechanisms—such as auditory cues (alerts, beeps), tactile signals (vibrations), or simple visual outputs—without requiring off-site processing. The benefits of this approach have been previously established: Pantelopoulos and Bourbakis (2010) surveyed wearable systems and emphasized the reliability of vital signs measurements and decision support for early detection of symptoms or context awareness, while Casson et al. (2021) demonstrated the feasibility of embedded EEG analytics, with some challenges.

The development of a near-infallible wearable sensor network for first responders is being anchored in a boot-based system that integrates multiple sensing modalities—including plantar pressure sensors, GPS, temperature probes, and potentially inertial measurement units. These smart boots are designed to function as both physiological and positional monitoring devices, capable of providing real-time insight into individual condition and team-level movement coordination under critical conditions. A key feature of this architecture is the capacity for local data processing and storage within the boot's embedded system, enabling field-level decision support without relying on continuous external connectivity.

Pressure sensors embedded in the sole of the boot can detect balance irregularities, gait asymmetries, or signs of fatigue. Real-time classification of such data on the device allows for early warnings of physical overload or fall risk, which can be communicated directly to the wearer via vibrotactile or auditory cues. Tao et al. (2020) demonstrated that gait disturbances can be effectively recognized using insole sensor arrays, especially when local microcontrollers are used to process pressure distribution patterns on-device, thereby reducing data transmission load. Crea et al. (2017) further validated that sensorized insoles, when combined with multimodal feedback mechanisms, enhance user awareness and reduce the likelihood of unnoticed physical degradation in dynamic operational contexts.

In addition to biomechanical data, boots in this system will include GPS modules for real-time location tracking and movement trajectory logging. GPS data are locally buffered and tagged with time-stamped physiological or thermal information to support downstream analysis of exposure, route difficulty, or time-on-task. Local storage and logic allow the system to function even when responders are in network-denied environments, with no risk of data loss. This architecture aligns with the edge-computing literature where physiological and spatial parameters are continuously collected and summarized directly at the sensor node to minimize bandwidth usage and reduce reliance on remote computation.

Temperature sensors integrated in the boot structure monitor ambient and internal microclimate conditions around the foot. This is critical in environments with intense radiant heat, such as during firefighting, where foot-level thermal data can indicate both environmental risk and potential failure of protective layers. Local processing of thermal readings allows for threshold-based alerts, providing users with proactive notifications before thermal stress escalates.

The system is designed to be opportunistically connected: when a stable communication link becomes available (e.g., proximity to a command post, portable router, or vehicle with uplink capabilities), the boots automatically offload stored data to a centralized platform. This event-based data transfer strategy ensures minimal impact on low-bandwidth links during operation while enabling rich, high-resolution data to feed into more computationally intensive analytics pipelines once the environment permits. This deferred transmission model enables support for longitudinal analysis, recommendation systems, and predictive risk modeling, without compromising the autonomy or resilience of the boots in the field.

By prioritizing local processing and selective synchronization, this boot-centric platform offers a robust and extensible foundation for physiological monitoring, situational awareness, and operational decision support under uncertain and infrastructure-limited conditions. It transforms the boot from a passive protective element into an active sensing and communication node—one capable of functioning intelligently, even in complete isolation.

A core feature of the near-infallible network is its ability to opportunistically interface with available communication infrastructure. When a stable connection becomes available—such as proximity to a base station, mobile router, or Wi-Fi access point—the stored data are automatically offloaded to cloud or edge servers. This synchronization replenishes local memory and triggers a secondary layer of processing that integrates the collected data into broader systems, including recommendation engines or situational analysis platforms. This two-tiered processing model ensures that high-volume raw data do not clog limited bandwidth channels during operations, while also allowing for enriched downstream analytics when resources allow. By allowing data to "travel later," when bandwidth is available, this approach ensures uninterrupted sensor operation during crises and then enables intelligent post-hoc analysis that can update safety models or support adaptive recommendations. This hybrid model—local, always-on analytics with asynchronous cloud connectivity—optimizes both resilience and intelligence in wearable systems. It aligns with the operational needs of emergency responders, offering robustness in isolated conditions while remaining extensible when full network infrastructure is accessible.

Skill Monitoring and Feedback Systems

The data collected by sensors, once integrated, provide critical information regarding the location and health status of first responders, including heat stress risk, and physical and mental workload. This information supports the generation of real-time alerts, instructions to act through biofeedback systems, precise location tracking for operational coordination and human resource management and facilitates the rescue of personnel in the event of occupational accidents.

Sensor data and health and safety risk information may be transmitted directly to first responders, providing real-time feedback to support decision-making and ensure personal safety. Additionally, emergency management organizations, such as Civil Protection agencies, can utilize this information to improve situational awareness, track responder movements within the operational area, and promptly detect scenarios requiring the rescue of injured or incapacitated personnel. However, this becomes a challenge in real emergency scenarios, particularly when communication systems are compromised.

Personal warning systems used by first responders typically include visual and tactile interfaces, such as an LCD screen, LED lights, or a vibrating element. These components provide immediate and clear alerts, allowing the professional to receive real-time notifications about potential risks or critical conditions. Although LCD displays can convey more complex messages, their effectiveness is compromised in high physical activity environments. Environmental conditions can also affect its effectiveness. Additionally, in dynamic environments, it can cause information overload and distraction.

More advanced solutions integrate e-textile technology directly into protective clothing, allowing for real-time monitoring of vital signs, posture, toxic gas concentrations, and environmental conditions. These systems include sensors, and a microcontroller embedded into an undergarment or protective suit, communicating wirelessly with a monitoring device. Alerts are provided through light and sound signals when thresholds are exceeded, maintaining responsiveness even in challenging environments. Some recent prototypes even incorporate AI-based predictive algorithms to warn of dangerous temperature changes before they occur, although these are still in development.

A notable example is the development of hierarchically sandwiched fabric (HSF) sensors that have recently been developed to simultaneously detect temperature and pressure under high-temperature conditions (up to 400 °C). These HSF sensors, integrated into conventional firefighting clothing, provide passive/active fire warning and spatial mapping of pressure and temperature, addressing the challenge of early fire detection and real-time motion sensing in extreme environments.

In addition to these visual and tactile alerts, auditory cues and noise reduction technologies have also been explored as critical tools to support firefighters' navigation and situational awareness. Pilot studies suggest that spatially placed auditory signals can aid orientation in smoke-filled environments, while noise reduction improves communication under high noise levels.

Moreover, recent frameworks have focused on integrating real-time bio signals monitoring with cognitive load estimation to enhance the safety and effectiveness of first responders in the field. These systems combine hardware and software to track bio signals such as heart rate, respiration, and eye gaze, analyzing how these indicators correlate with perceived workload through subjective tests. Although early trials have found variability in cognitive load responses, promising trends suggest that key bio signals can serve as proxies for mental workload. Such systems could allow dynamic adjustment of the information presented to first responders, reducing the risk of overload and improving decision-making in complex environments. Ultimately, by aligning the quantity and complexity of information provided with each firefighter's physical and cognitive state, these integrated frameworks can improve situational awareness and overall safety during emergency operations.

Beyond these cognitive load considerations, integrated architectures like the Internet of Cooperative Agents for search and rescue missions have demonstrated the potential of wearable sensor suites to monitor stress, anxiety, and physical fatigue in real-time during search and rescue missions. By combining measurements of cardiac electrical activity, electrodermal activity, piezoelectric signals, and brain electrical activity, these wearable systems enable continuous tracking of first responders' physiological states, providing critical insights for command centers and enhancing worker safety. Field tests with firefighters have validated the feasibility of these wearable designs (such as T-shirts, wristbands, and caps) and highlighted the importance of user acceptance and comfort in deploying these solutions in practice.

Complementing these efforts, intelligent systems such as the Stress Monitoring Assistant prototype have shown promise in providing reliable, individualized stress detection and monitoring for first responders (Lai et al., 2021). This assistant uses advanced machine learning techniques and a reasoning mechanism based on causal networks to accurately detect stress and support decision-making. Tested on comprehensive datasets, it demonstrates high accuracy in stress recognition, bridging current research and development gaps in decision support for extreme environments.

Ultimately, aligning sensor technologies, user needs, and operational contexts—while leveraging intelligent assistants that adapt to each responder—paves the way for safer, more effective responses in future disaster scenarios. Smartphones are useful tools for communication, and biofeedback solutions often use them to provide actionable recommendations for improving health and safety . However, they are unreliable when used alone in emergency scenarios . When sensor data is processed locally, tactile cues can be used as a means of emergency communication . Smartphones have been used to monitor firefighters' voice activity and body motion during training, revealing how communication patterns affect team performance. The same approach also tracked proximity and group dynamics using the smartphone's built-in ANT wireless protocol, achieving high accuracy when altitude data were included. Building on this work, the CoenoFire system collected extensive real-mission data from firefighters to provide temporal and behavioral metrics that support post-incident debriefings and training .

The role of first responders during a disaster response requires both technical skills (e.g., equipment operation, medical expertise, fire science, and safety protocols) and soft skills particularly those related to interpersonal interaction and effective communication. Tracking these skills during emergencies is critical for successful response efforts. Decision-makers must have clear visibility into responders' capabilities to allocate resources effectively, ensuring that the right personnel and equipment are deployed where they are needed most.

Information from different sources, such as human resource information systems, performance records, training programs, and certifications, can be extracted and integrated to provide a comprehensive view of personnel skills . Analyzing this integrated data enables organizations to ensure readiness, effectiveness, and safety in emergency response scenarios. It helps decision-makers understand the overall skill landscape, supporting informed decisions in response planning and resource allocation. Some existing solutions focus primarily on tracking firefighters' skills to support decisions related to training needs. However, other solutions go further by adressing operational readiness (see e.g. Acadis). Other systems monitor firefighters' vital signs and assist in allocating personnel to the emergency based on their current physical condition, helping to avoid potential risks to their safety and health. (e.g. FireCommand). The integration of data on responders' physical condition and wellbeing, along with their skill sets and real-time location on the scene, can significantly enhance decision-making by enabling the deployment of the most suitable personnel to each emergency.

Limitations of the wearable sensors and futures directions

Although wearable sensors have become standard components in firefighters' protective clothing, they still present significant limitations that hinder their effectiveness and safety. Main challenges include the formation of cracks in textile-based sensors, which compromises electrical conductivity and reliability. Gas sensors face particularly low detection thresholds (especially critical for explosive gases), while polymer-based gas sensors often suffer from reduced lifespans due to oxidative gases and ultraviolet radiation exposure. Additionally, these sensors exhibit extended recovery times, limiting real-time responsiveness in hazardous environments ,.

Worsening these difficulties, external factors such as body movements, ambient noise, environmental pollution, and mechanical vibrations interfere with signal accuracy. In humidity sensors, poor electrode durability resulting from current coating, deposition, and printing techniques further reduces reliability. Motion sensors also show reduced accuracy under constant movement and uniaxial stretching conditions, common in firefighting scenarios.

Given these limitations, future studies should prioritize the development of wireless, miniaturized, and self-powered sensing systems. Furthermore, these systems must be engineered to withstand environmental variables such as moisture, sweat, and radiant heat to ensure consistent and accurate performance in real-world firefighting conditions. Leveraging advances in nanotechnology offers a promising avenue to overcome these challenges, enabling next-generation wearable sensors with enhanced precision, stability, and adaptability.

Conclusion and Future Directions

Summary of Technological Advancements

The SIREN SoTA analysis underscores a transformative vision for disaster response. By integrating AI, LLMs, resilient communication, and physiological monitoring into a cohesive system, it lays the foundation for intelligent, agile, and human-aware emergency response networks. These advancements are critical to addressing modern disaster challenges and ensuring rapid, coordinated, and effective humanitarian aid delivery in the face of escalating climate and geopolitical crises.

Summary of key technological developments are as follows:

1. Large Language Models (LLMs)

Advanced AI models like GPT are being deployed to automate and accelerate disaster management processes:

- Generation of response plans and incident reports
- Real-time decision-making support
- Improved scenario analysis, communication, and resource allocation
- Integration of tools like Disaster GPT for simulation-based logistics planning

2. AI-Driven Decision Support Optimization

SIREN enhances decision-making through AI-powered systems capable of:

- Dynamic task prioritization and resource coordination
- Multi-objective optimization under uncertain conditions
- Real-time integration of environmental, logistical, and operational data streams
- Graph-based routing and team scheduling—even in disconnected environments

3. Agentic Emergency Communication Networks

To address limitations of current 3GPP standards, SIREN introduces:

- Autonomous, AI-driven communication architecture
- Real-time network reconfiguration
- Seamless integration of terrestrial and non-terrestrial systems
- Resilient and adaptive infrastructure for robust coordination during disasters

4. Physiological Monitoring & Wearable Technologies

New sensor-integrated PPE and wearables enable:

- Real-time health tracking (e.g., heart rate, fatigue, temperature)
- Edge-computing for local data processing and bandwidth efficiency
- Self-healing, peer-to-peer mesh networking for uninterrupted monitoring
- Skill mapping and responder performance assessment

5. Semantic 3D Mapping and Urban Profiling

Using technologies from Urban Hawk, SIREN delivers:

- Real-time semantic mapping and structural profiling
- Damage assessment and urban change detection
- Enhanced logistics and mobility planning based on evolving scenarios

6. Predictive Simulation & Scenario Modelling

By leveraging Polaron's simulation engine:

- Real-time "what-if" modelling with socio-cultural weighting
- Support for explainable, human-in-the-loop decision-making
- Enables strategic planning for evolving disaster contexts

7. Advanced Debris Management

AI-enabled tools support:

- Prioritization of clearance based on impact and sustainability
- Multi-team coordination and real-time tracking
- Integration with logistics intelligence for optimized deployment

Positioning Within Global SoTA Landscape

The SIREN project situates itself at the forefront of global innovation in disaster response, uniquely bridging gaps between isolated technological developments and fully integrated, operationally deployable emergency management systems. While many international efforts focus on specific domains—such as predictive modelling, AI applications, or communication infrastructure—SIREN distinguishes itself through a holistic, modular, and cross-sectoral approach that brings together these components into a cohesive, intelligent framework.

Global Comparison and Differentiators

- **Artificial Intelligence and LLM Integration:**
  While institutions such as the UN OCHA, NASA JPL, and MIT Lincoln Laboratory have advanced AI for logistics and risk modelling, their systems often lack real-time adaptability or full human-in-the-loop design. SIREN advances the state of practice by embedding context-aware LLMs (e.g., Disaster GPT) that generate, adapt, and prioritize action plans in dynamic scenarios. Unlike other platforms, SIREN combines semantic reasoning, sentiment analysis, and role-specific response synthesis to directly support frontline decision-making.
- **Agentic Communication Architecture:**
  Globally, 5G-enabled public safety networks and satellite-based communication systems (e.g., FirstNet in the U.S., TETRA-based systems in Europe) are being deployed for disaster scenarios. However, these often lack autonomous reconfiguration and AI-driven network intelligence. SIREN's agentic AI-based architecture goes beyond static systems by enabling self-healing, real-time, and context-sensitive network adaptability—representing a next-generation evolution in emergency communications.
- **Human Monitoring and Wearables:**
  Efforts such as those by the Defense Advanced Research Projects Agency (DARPA) and EU Horizon projects like RESPOND-A have explored responder wearables. However, SIREN uniquely integrates edge-computing capabilities, mesh-networked self-healing

communication, and skills-based performance profiling, offering a higher degree of autonomy and continuity in degraded environments.

- **Urban Profiling and Simulation:**
  Compared to global counterparts like Japan's NIED and Germany's DLR, which focus on geospatial intelligence and hazard mapping, SIREN integrates real-time semantic 3D mapping, urban change detection, and AI-enhanced simulation. This empowers decision-makers to dynamically anticipate and adapt to secondary effects and cascading failures during complex, multi-phase disasters.

- **Cross-Border and Multinational Synergy**

SIREN's multinational foundation and alignment with **EU Civil Protection Mechanism** goals position it as a blueprint for **cross-border, interoperable disaster response ecosystems**. Its design anticipates integration with future EU-led resilience platforms and can serve as a **reference model** for other global regions seeking to build collaborative, AI-enabled humanitarian infrastructures.

- **Strategic Alignment with Global Trends**

SIREN is fully aligned with global policy and research priorities, including:

- UN Sendai Framework for Disaster Risk Reduction
- EU Green Deal (via sustainable logistics and response planning)
- ITU and 3GPP initiatives on resilient communication
- OECD Future of Risk Management frameworks

By addressing both technological advancement and operational deployment challenges, SIREN not only pushes the boundary of what is currently feasible but also lays a scalable and ethical foundation for the next generation of disaster response systems.

Roadmap for Post-Project Innovation Transfer

To ensure that the advancements achieved within the SIREN project lead to meaningful, sustained impact beyond its initial research and development phase, a structured roadmap for innovation transfer has been developed. This roadmap outlines a multi-phase strategy to translate research outputs into operational tools, scalable platforms, and institutional capabilities for disaster response stakeholders at local, national, and international levels.

Phase 1: Validation and Demonstration (Immediately Post-Project)

- **Pilot Deployments**: Conduct real-world testing of integrated SIREN components (AI-driven decision support, physiological monitoring, semantic mapping, and communication systems) in collaboration with civil protection agencies and humanitarian organizations.
- **User Training and Capacity Building**: Develop training programs for first responders, disaster planners, and public safety officials to operate and adapt SIREN technologies.
- **Feedback Loops**: Establish structured feedback mechanisms with end-users to refine usability, performance, and interoperability in real-world disaster scenarios.

Phase 2: Institutional Integration and Policy Alignment

- **Standards Development**: Collaborate with international bodies (e.g., 3GPP, ITU, ISO, CEN) to contribute SIREN's innovations to emerging standards for emergency communications, AI ethics, and disaster resilience technologies.

- **Policy Engagement**: Work with EU Civil Protection Mechanism, UN OCHA, and national governments to integrate SIREN's outputs into disaster risk reduction policies and operational frameworks.
- **Cross-Border Coordination Protocols**: Promote SIREN's interoperable architecture as a reference model for multinational disaster collaboration platforms.

Phase 3: Commercialization and Open Technology Transfer

- **Modular Technology Licensing**: Enable commercialization of select SIREN components—such as the wearable physiological monitoring systems, Disaster GPT interface, and agentic network modules—through licensing or partnerships with industry players.
- **Open APIs and Developer Toolkits**: Release open-source SDKs and APIs to stimulate innovation by third parties and SMEs, particularly in the areas of decision support optimization and disaster logistics.
- **Incubation Support**: Facilitate start-up and spin-out ventures built on SIREN technologies through European innovation hubs and Horizon Europe commercialization programs.

Phase 4: Global Scaling and Replication

- **Replication in Climate-Vulnerable Regions**: Collaborate with international aid organizations and development banks (e.g., World Bank, UNDP) to adapt and deploy SIREN systems in climate-sensitive and resource-constrained regions.
- **Language and Cultural Localization**: Expand LLM-based interfaces to support multilingual, culturally aware deployments to ensure inclusive, equitable access to SIREN capabilities.
- **Long-Term Monitoring and Impact Assessment**: Establish a consortium-wide monitoring framework to track the operational, economic, and social impact of SIREN deployments over a 5–10 year horizon.

Strategic Objectives of Innovation Transfer

This roadmap ensures that the SIREN project transitions from an R&D initiative into a strategic enabler of next-generation disaster resilience. The focus is on:

- Operationalization of AI, LLMs, and resilient communication systems
- Institutional adoption through alignment with existing emergency frameworks
- Market readiness via modular commercialization
- Sustainability and scalability through global partnerships and capacity building

Ultimately, the SIREN roadmap ensures that the scientific breakthroughs achieved do not remain confined to academia but evolve into practical, deployable, and high-impact solutions capable of transforming global disaster response capabilities.

Recommendations for Policy and Adoption

To translate the innovations of the SIREN project into widespread and sustainable impact, a strategic alignment between technology development and policy frameworks is essential. The following recommendations are intended to support policymakers, regulatory bodies, emergency response agencies, and international organizations in adopting, integrating, and scaling SIREN technologies to build more resilient, adaptive, and effective disaster response systems.

1. Establish Regulatory Pathways for AI-Driven Disaster Management

- Define Ethical and Operational Standards for the use of Large Language Models (LLMs), predictive simulations, and agentic AI in disaster response. This includes ensuring transparency, explainability, and accountability in automated decision-making processes.
- Create Certification Protocols for AI-driven decision-support systems to validate safety, accuracy, and compliance under dynamic and high-risk emergency scenarios.
- Promote Human-in-the-Loop Systems to balance autonomy with expert oversight, particularly for decisions affecting lives, public safety, or critical infrastructure.

2. Accelerate the Integration of Resilient Communication Architectures

- Mandate Interoperability Standards across national and cross-border emergency networks to ensure seamless data and voice exchange during disasters. This includes alignment with 3GPP evolution and the adoption of agentic AI-based network coordination.
- Incentivize Investment in Intelligent Communication Infrastructure, including autonomous, self-healing mesh networks that maintain operability in degraded environments or in the absence of central infrastructure.
- Promote Dual-Use Capabilities to support both civilian and military/humanitarian coordination through shared, secure communication backbones.

3. Embed Physiological and Skills Monitoring into Workforce Protection Policies

- Adopt Standards for Health-Aware PPE that incorporate real-time physiological monitoring for first responders and emergency workers.
- Introduce Occupational Safety Regulations that support the deployment of wearable health systems, especially in high-risk, high-fatigue environments such as wildfires, urban search and rescue, and conflict zones.
- Include Health-Driven Deployment Guidelines, where responder dispatch and task assignment are informed by physiological readiness and mental strain indicators.

4. Encourage AI and Simulation Integration in Disaster Planning

- Mandate Scenario-Based Training and Planning using simulation engines and digital twins as part of national and regional emergency preparedness programs.
- Update Civil Protection Protocols to include AI-assisted scenario analysis, resource allocation modeling, and mobility simulation, particularly for urban and climate-sensitive zones.
- Fund Localized Adaptation of Simulation Tools to reflect geographic, social, and cultural variables that affect disaster response outcomes.

5. Support Data Governance and Federated Intelligence Models

- Establish Secure Data-Sharing Frameworks between emergency response actors, enabling the ethical and efficient use of real-time, multi-source data (e.g., social media, satellite, IoT).
- Encourage Federated Learning and Decentralized AI Models that respect data sovereignty while improving cross-agency learning and interoperability.
- Protect Sensitive Data in compliance with GDPR and global data protection regulations, particularly for health and behavioral insights collected through monitoring systems.

6. Prioritize Equity, Access, and Localization in Technology Deployment

- Ensure Accessibility of SIREN Tools to low-resource regions, marginalized communities, and vulnerable populations through scalable, low-bandwidth, and language-adaptive interfaces.
- Promote Community-Centered Design by engaging local responders, NGOs, and affected populations in system customization and feedback loops.
- Incentivize Localization Efforts that adapt AI models, communication protocols, and decision-support platforms to diverse cultural, linguistic, and regulatory contexts.

7. Align Funding and Innovation Policy with Disaster Resilience Goals

- Embed Disaster Tech as a Priority Area within national R&D programs, EU Horizon Europe missions, and global development aid portfolios.
- Support Public-Private Partnerships to accelerate the commercialization and deployment of SIREN innovations, including AI, wearables, and intelligent communication solutions.
- Provide Post-Project Innovation Incentives through procurement frameworks, pre-commercial pilot programs, and innovation sandboxes for disaster response applications.

Adopting the SIREN project's technologies at scale requires more than technical readiness—it demands **proactive policy alignment, cross-sector collaboration, and forward-looking governance**. These recommendations serve as a foundational guide for transforming SIREN's innovations into institutional capabilities, ensuring that emergency response systems across Europe and beyond are prepared not just for today's crises but for the increasingly complex disasters of tomorrow.