

Methods of Interoperability and Integration of Disaster Management Systems

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ABSTRACT

The Tehran Municipality Disaster Mitigation and Management Organization operates multiple independent systems for earthquake disaster response, each with separate databases. This isolation leads to inefficiencies and increased complexity in seismic disaster management. This paper explores solutions to integrate and enable interoperability among these systems by comparing architectures such as microservices, service-oriented architecture (SOA), enterprise service bus (ESB), and event-driven architecture (EDA). The recommended approach combines microservices with technical interoperability using REST APIs, API Gateway, and Graph Query Language (GraphQL). The study emphasizes technical interoperability and suggests employing Extract, Transform, Load (ETL) processes to consolidate spatial and non-spatial data into a central database. To improve semantic interoperability, ontology-based data preprocessing is proposed. Integrating system and spatial data enhances stability, scalability, and preparedness in disaster management. Due to security constraints, the proposed framework remains theoretical and untested in operational settings. While direct validation was not possible, the solution is supported by comparative analysis of existing models and best practices. The key innovation is the hybrid use of microservice architecture with GraphQL, tailored for heterogeneous spatial and non-spatial systems in disaster management. This paper offers a modular, scalable, and semantically aware integration framework to inform future system implementations and policy decisions in seismic disaster response. A case study from Tehran Municipality District 2 illustrates the model's relevance by highlighting spatial vulnerabilities such as aging buildings, population density, and fragmented geospatial layers, demonstrating real-world challenges and the necessity for the proposed architectural solution.

1. INTRODUCTION

Interoperability of information systems in today networked and globalized world is essential for the success and even survival of organizations. This capability can enable the provision of more diverse and integrated services, reduce operational costs, and improve organizational efficiency (Soares and Amaral, 2014). Disaster management requires the interaction of multiple factors to prevent damage and respond to hazards. This involves exchanging information to provide a rapid, integrated response. Time is the most critical factor in this process (Casado et al., 2015b). In time-sensitive situations, utilizing efficient and accessible data systems is vital for effective decision-making. Disaster management demands collaboration among organizations like police, fire services, and health services, with seamless information exchange and real-time communication being crucial for a swift and coordinated response (Da Silva Avanzi et al., 2017). The field of Geospatial Information Systems is an interdisciplinary field that integrates information technology, spatial analysis, and data management to support informed spatial decision-making (Reddy, 2018). This research naturally falls at the intersection of three key areas including spatial data, information technology, and disaster management (Singh, 2024). However, what makes Geospatial Information Systems (GIS) the best option for conducting this research is its interdisciplinary and specialized nature in measuring, mapping, managing, modeling, and monitoring georeferenced data (Reddy, 2018). GIS offers a practical and analytical approach to

understanding the spatial needs of decision-makers in disaster situations, enabling the design of intuitive dashboards that simplify complex information for non-technical users (Han and Choi, 2024). While other fields may cover parts of this path, none of them alone encompasses the comprehensive spatial perspective needed for such a project (Ghosh, 2023). Implementing GIS in this research is both logical and necessary, as it provides a technical, analytical, and decision-making framework to extract valuable insights from diverse data, enabling rapid and effective disaster response. (Vasdev, 2019). This research addresses integration challenges in Tehran's fragmented disaster management systems, focusing on independent specialized systems like Accelerograph, Damage Estimation, and Thematic Mapping, which hinder efficient disaster coordination. This research aims to answer the following key questions:

- What are the main challenges of existing systems in terms of interoperability, standardization, and data quality from a geospatial perspective?
- How can these systems be technically integrated and made interoperable without disrupting their core functionalities?
- To what extent can a unified dashboard improve the effectiveness and efficiency of disaster response?

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The primary objective is to analyze and propose technical and semantic solutions for integrating and enabling interoperability among specialized disaster management systems. The study assumes that all systems under investigation are currently operational. However, due to organizational security restrictions, direct access to these systems was not permitted, and practical implementation was not feasible. Consequently, the research was conducted at a theoretical and conceptual level, focusing on architectural modeling and best practices. Expected outcomes include a conceptual framework for system-level integration, identification of key interoperability barriers, and recommendations for future implementation. The rest of the paper includes fundamental concepts in Section 2. Section 3 presents literature review. Section 4 covers research methodology. Section 5 elaborates case study and Section 6 concludes the paper and recommends some directions for future research.

2. FUNDAMENTALS CONCEPTS

This section describes Tehran earthquake-specific systems (Accelerograph, Damage Estimation, Thematic Mapping) and presents a framework for system integration and interoperability, including definitions, differences, and levels of technical, semantic, and organizational interoperability in disaster management.

2.1 Disaster Management Systems: Tehran Disaster Management and Mitigation Organization (TDMMO) 58 systems (25 general, 33 specialized) with varying interoperability, databases, and formats. This complexity hinders decision-making during crises. Integrating geospatial data and systems could resolve these issues and improve the process (Tehran Municipality Report, 2023). Several specialized earthquake disaster management systems in the TDMMO are implemented which are described in the following section.

- **Accelerograph System:** This system is used to receive data from stations shared with the Ministry of Roads and Urban Development, and then transfer this data to the SeisComp software. It lacks a database; the software is solely used for data transfer and its storage capability is not utilized within the organization (Tehran Municipality Report, 2023)(Figure 1).

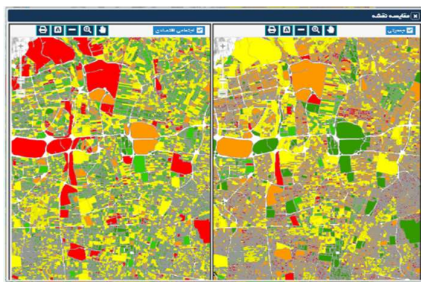


Figure 1. Accelerograph System (Tehran Municipality Report, 2023)

- **Earthquake Damage Estimation System:** This system receives accelerometer data and calculates the resulting seismic damages and casualties. Currently, the necessary data for the system is uploaded offline, and updating this data requires a significant amount of time. In addition, the generated outputs cannot be used online in other systems (Tehran Municipality Report, 2023)(Figure 2).

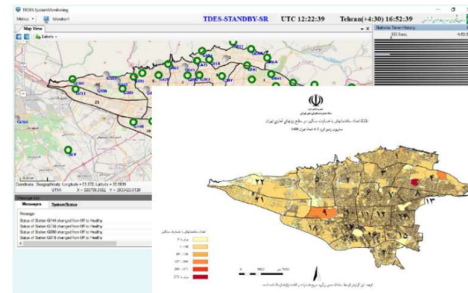


Figure 2. Earthquake Damage Estimation System (Tehran Municipality Report, 2023; Lauras et al., 2015)

- **The Thematic Maps System:** This system includes spatial data available in Tehran Municipality such as buildings, land use, population, and critical arteries, with the ability to compare maps. Given the capability to compare indices on the map, defining various scenarios is possible. Currently, only the output of the neighborhood risk assessment is uploaded in this system (Tehran Municipality Report, 2023)(Figure 3).

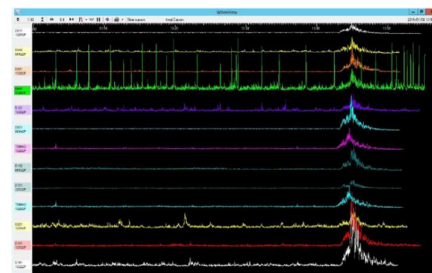


Figure 3. The Thematic Maps System (Tehran Municipality Report, 2023; Itria et al., 2014)

2.2 Systems Interoperability and integration : System interoperability means "collaboration and information exchange between systems without major changes in their structure and functionality", while integration means "combining software, hardware, or both into a comprehensive system and fully merging systems with significant changes in their structure and functionality" (Soares and Amaral, 2014). Integration involves collecting data from various sources, and their transformation, harmonization and storage in a central database to be displayed in a unified and coordinated manner on a dashboard. Information and Communication Technology (ICT) systems play a crucial role in managing and sharing vital information (Casado et al., 2015). Advances in information technology (IT) capabilities significantly enhance internal and external information sharing within organizations. The faster and more securely managers receive information, the better they can implement strategies. This need is met through technological capabilities, and with proper use of these facilities, an integrated system for managing and distributing information assets can be created, contributing to the organization future development (Balaghi, 2021).

2.3 Interoperability Layers: The concept of interoperability is defined at various levels and layers (Lemmens, 2006):

-Technical Interoperability: The ability of systems to communicate and exchange data using common technical protocols and standards.

- Semantic Interoperability: The ability of systems to understand and interpret concepts and data in a consistent manner.

- Organizational Interoperability: Coordination and agreement between and among organizations regarding processes, policies, and methods of information sharing.

Each of these interoperability layers can be examined in detail, as each has its own challenges, technologies, standards, and frameworks. At the technical interoperability layer, the concepts generally take on a technical aspect and are closely related to methods of enterprise application integration. "Integrated systems are necessarily interoperable, but interoperable systems are not necessarily integrated (Nazemi, 2020; Chen et al., 2008).

In this study, the focus is initially on a brief review of the concept of semantic interoperability, followed by a primary focus on the concept of technical interoperability and integration in seismic vulnerability assessment.

2.4 Challenges Of Non-Interoperability and Non-Integration Of Systems: Information sharing and coordination among emergency forces and managing large volumes of information in a highly dynamic environment is one of the most challenging tasks in disaster management (Casado et al., 2015). Some of these challenges include:

- Existing systems use different technologies and programming languages (Khan et al., 2023).

- Diverse data sources stored in various formats across different databases. Some data are real-time, while others require offline processing (Akter and Wamba, 2019).

- Lack of system interoperability and inability to share data and information among stakeholder organizations (Gençtürk et al., 2018).

- Lack of scalability and extensibility, with many systems being outdated and requiring revision and expansion (Noran, 2013).

2.5 Types of System Integration Methods: In modern distributed and heterogeneous information systems (such as those used in disaster management) the integration of various subsystems is essential for ensuring operational continuity, data exchange, and scalability. As system complexity and diversity increase, selecting the appropriate integration architecture becomes a critical design decision (Weerasinghe and Perera, 2021). Various architectural patterns have emerged over time to enhance system interoperability, each offering distinct benefits and drawbacks in terms of scalability, maintainability, fault tolerance, and real-time performance. These range from traditional middleware solutions like Enterprise Service Bus (ESB), to modular frameworks such as Service-Oriented Architecture (SOA), and extend to contemporary, agile models like Microservices and Event-Driven Architecture (EDA) (Banerjee, 2024). These architectural approaches mark a transition from rigid, synchronous systems to more flexible, asynchronous, and event-driven setups. This shift is particularly significant in dynamic fields such as disaster response, where immediate actions and uninterrupted availability are essential. (Phutharak and Loke, 2023). The following section provides a comparative overview of these system integration methods.

- Enterprise Service Bus (ESB): ESB is a middleware layer in SOA architecture that connects various services, routes messages, and coordinates them, acting as the core or "chassis" of SOA architecture. ESB manages services through specific protocols like : Simple Object Access Protocol (SOAP) and provides features such as data transformation, security, and message flow control (Weerasinghe and Perera, 2021). However, it has complexities in implementation and maintenance and may create a single point of failure, which is undesirable for modern distributed architectures (Banerjee, 2024).

- Service-Oriented Architecture (SOA): SOA is a software architecture where applications are built as a collection of independent services that interact through intermediaries like ESB. The goal of SOA is to separate functionalities into independent services that can be developed, managed, and scaled in a distributed manner (Weerasinghe and Perera, 2021). SOA was later introduced as an architecture to improve and complement ESB (Banerjee, 2024).

- Micro services: Micro services is a modern approach to design and develop large software systems by dividing them into smaller, independent services. In the context of disaster management, each microservice may handle a specific task, such as alert dissemination, volunteer or resource registration, or victim status tracking-and all these services communicate through APIs (Banerjee, 2024; Laurus et al., 2015). The main advantage of this architecture is that each service can be developed, updated, or even changed to a different technology independently without affecting other systems. This means high flexibility, faster development and deployment of new features (such as real-time data dashboards or evacuation alerts), and better scalability to meet dynamic and unpredictable disaster scenarios (Itria et al., 2014; Banerjee, 2024).

- Event-Driven Architecture (EDA): To complete the evolution cycle, we initially had Message-Oriented Middleware (MOM); this concept has re-emerged as Event-Driven Architecture. This architecture includes modular and distributed components that facilitate interaction between various data and services. The system is capable of reacting to events in real-time and supporting complex event processing (Phutharak and Loke, 2023). Event-Driven Architecture excels in its inherent flexibility, enhancing system scalability, adaptability, and resilience. In earthquake disaster management, EDA enables real-time event handling, such as immediately triggering alerts, activating sirens, and dispatching responders when a seismic sensor detects significant ground motion. Simultaneously, less critical tasks like logging, dashboard updates, or public notifications can occur asynchronously, ensuring uninterrupted real-time response. This separation of critical and non-critical processes boosts system reliability and scalability in high-stakes, dynamic situations (Itria et al., 2014; Laurus et al., 2015). The ability to process transactions asynchronously, without waiting for responses, supports scalability and enhances user experience. While SOA with SOAP APIs was advantageous for integrating legacy systems, it had limitations in service discovery and lacked the lightweight nature of REST APIs. Today, REST APIs, microservices, and event-driven architectures are crucial for modern software development, but organizations must carefully choose and implement these approaches to suit their specific needs (Banerjee, 2024) (Table 1).

Feature/Methods	ESB	SOA	EDA	Microservices
Base Architecture	Central Bus	Service-Oriented	Event-Driven	Independent Small Services
Scalability	Medium	Medium	Very High	Very High
Agility in Development and Deployment	Low	Medium	High	Very High
Suitable for Real-Time Data	Weak	Weak	Excellent	Good (when combined with EDA)
Suitable for Heterogeneous Systems	Excellent	Good	Excellent	Good
Maintenance and Complexity	Complex	Medium	Complex	Medium
Suitable for Real-Time Dashboard	Not Much	Limited	Yes	Yes (when combined with API and EDA)

Table 1. Comparison of System Integration Methods (Banerjee, 2024; Phuttharak and Loke, 2023; Weerasinghe and Perera, 2021)

3. LITERATURE REVIEW

Azizah and Wijayanto (2023) developed an interactive web-based dashboard for visualizing flood vulnerability indices using satellite imagery. The method integrated spatial data and utilized the qgis2web plugin to convert geospatial layers into HTML, JavaScript, and CSS. The resulting dashboard aids government to monitor high flood vulnerability areas and supports decision-making to reduce risk in these regions.

Casado et al (2015) developed a software solution to address cultural, linguistic, and technical differences in European disaster management systems, aiming to enhance interoperability and information exchange during emergencies. Utilizing semantic technologies and SOA, they created a common ontology to model disaster-related concepts universally. The system acted as an intermediary for data exchange, translating various formats and protocols. Tested via a pilot implementation of a border fire between the Netherlands and Germany, the SOA-based architecture with a central core and mediators (Mediator Pattern) employed web services (WS) including RESTful APIs for ontology access (EMERGEL) and data transfer using web standards (Web Map Service (WMS) and Web Feature Service (WFS)). The solution demonstrated reduced response times and increased collaboration among entities in disaster management.

Ding et al. (2015) designed an Integrated GIS (IGISS) aimed at improving natural disaster management. This system combines diverse spatial data sources such as satellite imagery, vector data, and real-time information, enabling more accurate and faster decision-making process. The system implementation used SOA and web-based technologies like WMS and WFS. Case studies on several natural disasters in China tested the system performance, and the results showed that this solution has high capability in integrating and accessing information. The system was able to meet the needs of organizational users in emergency situations effectively. The authors suggested that this system be developed further, using cloud technologies and disaster prediction algorithms. They also emphasized the importance of designing user-friendly interfaces for non-specialist users.

Masmoudi et al. (2018) presented a semantic and service-oriented platform called PREDICAT, which helps integrate diverse and scattered Earth observation data and predict disasters. This platform uses SOA and semantic models (MEMOn ontology) to semantically integrate and link heterogeneous data. Data from various sources with different formats (such as CHIRPS and OpenWeatherMap) are extracted using RESTful services and semantically enriched. Then, the data are integrated into: Resource Description Framework (RDF) format, and disaster prediction is performed using semantic learning and inference rules. The results show that the platform can facilitate access, integration and analysis of large Earth observation datasets. Finally, it was suggested to expand to social media data and improve data quality metrics for the future.

4. RESEARCH METHODOLOGY

There is no single, universal approach that is suitable for all organizations. Organizations typically need to select a combination of these methods based on their needs and technological maturity. Using ESB has its own advantages and disadvantages and is suitable for organizations with large and advanced architectures, however, it may not be suitable for some environments due to complexity and the risk of a single point of failure. SOA with SOAP was a significant advancement, however, due to its heaviness nature, it was replaced by REST and Micro services. Micro services architecture and REST APIs, along with EDA, are preferred for modern systems in terms of scalability, extensibility, and agility. The most important point is to consider a combination of technology and processes for successful system integration implementation (Nadareishvili et al., 2016; Newman, 2021). Given the nature of the project, which includes several heterogeneous internal and external systems with spatial and non-spatial data and real-time information displayed in a disaster management dashboard, the combination of Micro services architecture and REST API will be the best option. This architecture, using API Gateway, REST API, and GraphQL, enables the integration of heterogeneous geospatially referenced data, supports connection to management dashboards, and provides high extensibility for the future. In addition, if stronger real-time event processing is needed, EDA architecture can be used as a complement in some sections.

REST APIs: REST APIs are used for system integration. They follow REST architectural principles and use the HTTP protocol (such as GET, POST, PUT, DELETE for various operations) for communication between and among systems. These APIs are widely used for system integration in web and mobile applications due to their lightweight, simplicity and flexibility (Danišls, 2023). Combining these two methods allows organizations to implement their systems in a coordinated and scalable manner. Each micro service provides a REST API that allows clients and other micro services to communicate with it. This combination helps organizations benefit from the advantages of both methods and implement their systems effectively and maintainable. Moreover, since micro services are independent of each other, if one part of the system encounters a problem, the entire software does not fail, and only that specific service needs to be fixed. For this reason, many large companies like Netflix, Amazon, and Google have adopted this architectural style to provide their services faster and better (Banerjee, 2024).

API Gateway is the central connection point for micro services and incoming requests and can manage security, logging, and access control. Some advantages of using API Gateway include (Oktaria et al., 2021):

- **Authentication and Authorization:** acts as a central entry point to manage user authentication and authorization, eliminating the need for each microservice to handle it, thereby enhancing security.
- **Traffic and Load Management:** Reduces network traffic by aggregating requests and routes them simultaneously to the appropriate microservices, adjusting the number of active instances based on load.
- **Access to Dashboard and Central Database:** Clients connect to dashboards and central databases through the API Gateway rather than directly accessing microservices, improving security and efficiency.
- **Caching Capability:** Utilizes temporary data storage to increase response speed and reduce operational costs.

5. CASE STUDY

Due to organizational security restrictions, practical implementation of the proposed framework was not possible. Therefore, this study adopts a conceptual and architectural approach to examine the integration of heterogeneous disaster management systems. As a theoretical case study, Tehran Municipality District 2 was selected. This region is located adjacent to the North Tehran fault in its northern part and includes aged and vulnerable urban fabric in the south, making it a high-risk area in terms of earthquake vulnerability and a suitable subject for conceptual analysis. The proposed integration framework is designed based on Microservices architecture, RESTful APIs, API Gateway, and GraphQL, aiming to integrate both spatial and non-spatial systems. The data preparation and loading processes are supported by ETL techniques, while ontology-based semantic interoperability is used to harmonize heterogeneous data sources.

The real data used in the conceptual design included key spatial and structural indicators relevant to urban disaster management: average number of floors per building block, average slope, building density, structural quality, area of each block and proximity to the North Tehran fault.

System performance evaluation was conducted theoretically, based on a systematic review of prior studies, technical documentation of similar architectures and a comparative analysis of the proposed model against the operational requirements of urban disaster management.

Given the lack of a practical system implementation, no quantitative results (such as numerical performance measurements for latency, reliability, or data throughput) were produced. However, the qualitative assessment indicates that the proposed architecture aligns well with the data conditions, structural characteristics, and disaster seismic physical vulnerability of Tehran Municipality District 2. It conceptually demonstrates the potential to improve system interoperability, resilience, and decentralization.

Therefore, the framework is conceptually validated, relying on consistency with established software architecture principles and empirical insights from similar documented projects. It may serve as a sound foundation for future implementation or prototyping in real-world disaster management systems. Figure 4 illustrates the research architecture.

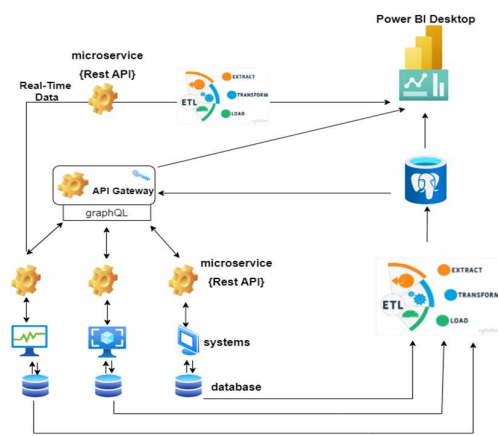


Figure 4. Research Architecture

6. CONCLUSION and RECOMMENDATIONS

This study developed a technical and semantic interoperability framework for integrating disaster management systems in Tehran Municipality. Due to organizational limitations, only a theoretical evaluation was conducted, analyzing existing architectures and literature. The proposed framework, based on Microservices, RESTful APIs, API Gateway, and GraphQL, aligns conceptually with the organization operational, semantic, and technical needs. Real spatial indicators from Tehran Municipality District 2 supported the architectural modeling. The study builds upon and extends earlier works (Azizah and Wijayanto, 2023; Casado et al., 2015a; Ding et al., 2015; Fan and Zlatanova, 2011) which focused on semantic interoperability and SOA for disaster management. While prior systems relied primarily on SOA and centralized ontology platforms, the current framework integrates semantic tools with real-time API-based technical structures to address both data-level and architecture-level fragmentation.

In response to research questions with respect to the main challenges of the research, lack of interoperability, heterogeneous data formats, semantic inconsistency, and outdated systems can be mentioned. Concerning the methodology to integrate the systems without functional

disruption, it is claimed that by using modular Microservices with REST APIs and API Gateway, each system can operate independently while remaining integrated. Regarding the improved performance using a unified dashboard, it is found that using GraphQL and ETL processes enables fast, selective, and real-time data retrieval for dashboards, reducing latency and decision time.

The framework successfully addressed the core objective of designing a flexible and scalable integration model. It supported both technical interoperability (via APIs) and semantic interoperability (via ontology-based ETL), covering spatial and non-spatial data flows. Although no formal statistical hypothesis testing was conducted, the conceptual alignment of the proposed solution with architectural best practices, domain requirements, and disaster-specific constraints serves as a strong conceptual validation of the research assumptions.

The proposed model is scalable and can be adapted to other urban areas with similar fragmented systems and spatial risk profiles. Its modularity allows future enhancements without structural redesign. The novelty of the research includes, the integration of Microservices and GraphQL with ontology-based ETL for disaster management; conceptual case study tailored to Tehran Municipality District 2 using real spatial indicators and emphasis on both system-level and data-level interoperability for resilience. The proposed model offers a decoupled architecture with high flexibility, faster response times, reduced latency, clear semantic data integration, and resilience against subsystem failures. However, the study lacks quantitative performance data due to no real implementation, limited access to seismic systems for validation, and the ontology was not practically deployed. Future research should include pilot implementation with synthetic data, ontology extension using standard vocabularies, stakeholder involvement for design feedback, and integration of real-time sensor data using EDA to enhance scalability.

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