

Supplementary Material 1: Comprehensive Summary of the PhD Proposal

This research proposal, titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration," is conducted at the Digital Systems Department of University X. The PhD aims to address the critical challenges faced by first responders in rapidly evolving emergency scenarios by developing a decision-support framework that integrates diverse data sources, validates their reliability, and leverages predictive analytics to provide actionable insights.

A preliminary literature review revealed substantial gaps in the current systems designed to support first responders during emergencies. Despite the availability of extensive data from both traditional sources, such as environmental sensors and infrastructure feeds, and nontraditional sources, including social media and citizen-generated reports, existing systems fail to seamlessly integrate these heterogeneous streams. This fragmentation complicates situational awareness and slows down critical decision-making processes. The review also identified a lack of mechanisms to validate nontraditional data, further diminishing the reliability of the information available to responders.

These findings align with the analysis conducted by the International Forum to Advance First Responder Innovation (IFAFRI), particularly Capability Gap 4. This analysis underscores the difficulty of incorporating information from diverse and nontraditional sources into incident command operations. Key challenges identified include inconsistent data formats, the absence of real-time validation mechanisms, and a lack of adaptable interfaces that allow responders to prioritize and customize information according to situational needs.

Motivated by these challenges, this research seeks to design, develop, and evaluate a novel framework that integrates predictive analytics and advanced data harmonization techniques. The proposed system will focus on three key objectives. First, it will establish a scalable architecture to integrate heterogeneous data sources, ensuring compatibility across diverse formats and enabling seamless communication among disparate systems. Second, the framework will incorporate real-time data validation mechanisms to assess the credibility of information from nontraditional sources. Finally, predictive analytics models will be employed to identify patterns, forecast incident evolution, and support proactive decision-making.

The methodology will involve designing a user-centric system that provides first responders with customizable interfaces, enabling them to prioritize information dynamically during high-pressure situations. By combining machine learning techniques with advanced data processing, the system will deliver tailored insights that enhance situational awareness. The framework will be evaluated through iterative testing in simulated and real-world disaster scenarios to assess its effectiveness in improving decision-making speed and accuracy.

This research represents a significant step toward addressing the technological and operational gaps identified in the literature and by organizations like IFAFRI. By

providing first responders with a reliable, adaptable, and predictive decision-support tool, the project aims to redefine how emergency response teams interact with complex data environments. The outcomes of this research will not only enhance the effectiveness of disaster management operations but also contribute to the broader field of public safety innovation, aligning with the mission of the Digital Systems Department of University X to develop cutting-edge computational solutions with tangible societal impacts.

Supplementary Material 2: The Assessment of the PhD proposal by the Academic Advisor

In September 2023, the Thessaly Region of Greece faced a catastrophic natural disaster as Storm Daniel delivered over 700 mm of rainfall within just 48 hours, resulting in unprecedented flooding. This event tragically claimed 18 lives and caused the loss of 235,569 livestock, alongside extensive damage to properties and infrastructure. Approximately 72,951 hectares were submerged, impacting around 28,000 people. Post-disaster inspections revealed that 69.89% of the buildings had sustained damage, while 40.7% of affected infrastructure was destroyed or suffered significant structural and non-structural harm. The total damages exceeded €2 billion.

This disaster exposed critical deficiencies within Greece's disaster management framework. A preliminary flood risk assessment uncovered a highly fragmented system of both centralized and decentralized authorities responsible for flood response and management. At the national level, the Ministry of Environment oversees flood management programs, with the Secretariat for Natural Environment and Water facilitating inter-agency coordination. However, on the ground, decentralized Water Departments and Civil Protection Departments execute these programs, leading to overlapping responsibilities. In the Thessaly Region, this fragmentation was even more pronounced, involving municipalities, approximately 50 land improvement organizations, and the regional authorities of Larissa, Karditsa, Trikala, and Magnesia, all operating without a central coordinating entity. This lack of cohesion significantly hampered disaster response efforts.

The institutional and organizational fragmentation revealed systemic weaknesses, including inadequate coordination, poor information exchange, and insufficient oversight of operational protocols. These shortcomings led to delays in developing effective flood management strategies, with actions often misaligned with the region's hydrological realities. This case exemplifies a broader challenge within disaster risk management (DRM) systems worldwide: the lack of unified strategies and coordination undermines the ability of first responders to act swiftly and effectively in the face of natural disasters.

Motivated by the lessons learned from Storm Daniel and the systemic gaps it unveiled, this study aims to advance disaster response strategies by advocating for an integrated approach. Central to this vision is enhancing coordination and improving information sharing among all stakeholders involved in disaster management. While the immediate focus is on strengthening the resilience of the Thessaly Region, the study aspires to

provide actionable insights that address similar challenges globally, contributing to the development of more resilient societies capable of mitigating the impacts of future natural disasters.

Supplementary Material 3: ChatGPT prompts for the primary analysis

Supplementary Material 3-1: Naive

Please analyze the following PhD proposal titled “Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration”. Based on the proposal, provide recommendations on how the student should approach the research, including suggested methods, key steps, and potential challenges. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

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Output

The proposed research, "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration," addresses a critical need in emergency response by focusing on integrating diverse data streams and enhancing decision-making through predictive analytics. To effectively approach this research, the student should begin by prioritizing a comprehensive mapping of existing data sources, categorizing them into traditional and nontraditional streams, and identifying their specific attributes, such as reliability, accessibility, and format variability. This process could include semantic harmonization to align heterogeneous data formats and ensure seamless interoperability. Employing ontology development or adapting existing semantic frameworks could formalize relationships between disparate data streams, creating a unified and machine-readable structure for integration.

The research would benefit from employing a hybrid approach that combines advanced machine learning techniques with domain-specific knowledge to design predictive analytics models. These models should not only forecast incident evolution but also provide interpretable insights that are actionable under the high-pressure conditions faced by first responders. Special attention should be given to real-time data processing and latency reduction, as timely information is paramount in emergency scenarios. Furthermore, the development of algorithms for validating nontraditional data sources, such as social media and citizen-generated reports, is a key component of this framework. These algorithms could leverage natural language processing to analyze textual data, cross-reference information across multiple sources, and assign credibility scores to ensure the reliability of insights presented to responders.

The user-centered design aspect of the proposed system is particularly critical. The interfaces should be adaptable to the varying needs of responders, allowing for dynamic prioritization of information. Incorporating features such as visual analytics, customizable dashboards, and intuitive controls would enhance usability and reduce cognitive load during crises. Iterative testing with first responders in both simulated and real-world disaster scenarios should be central to the development process, ensuring the system aligns with the practical demands of emergency operations.

Given the emphasis on data integration, the student should also address the challenges of interoperability between existing systems and the proposed framework. This includes ensuring compatibility with legacy systems, developing scalable solutions for data harmonization, and adhering to international standards for information exchange in disaster management contexts. Moreover, the incorporation of ethical considerations, such as data privacy and the responsible use of predictive analytics, will strengthen the broader impact and acceptance of the research.

Overall, this proposal demonstrates a strong alignment with identified technological gaps, particularly those highlighted by IFAFRI. By systematically addressing the challenges of data integration, validation, and user-centered design, and by leveraging predictive analytics to enhance situational awareness, this research holds significant potential to advance the field of disaster management and public safety. The student's approach should remain iterative and adaptive, continuously refining the framework based on empirical findings to ensure its practical efficacy and societal relevance.

Supplementary Material 3-2: Keyword by PhD supervisors

Please analyze the following PhD proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration". Based on the proposal, provide recommendations on how the student should approach the research, including suggested methods, key steps, and potential challenges. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

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Please structure the recommendation using the keywords provided below:

- Predictive Analytics
- Decision Support Systems
- Data Integration
- Emergency Response
- Real-Time Validation
- Situational Awareness
- Heterogeneous Data Sources
- Machine Learning
- Disaster Management
- Public Safety Innovation

Output

The proposed PhD will prioritize data integration by establishing a scalable architecture capable of handling heterogeneous data sources, ensuring compatibility across diverse formats and enabling seamless communication among disparate systems often used in emergency response scenarios. By creating a unified platform, responders will gain access to a comprehensive data ecosystem, breaking down silos that impede effective decision-making. To further enhance interoperability, the implementation of standardized protocols for data exchange is recommended, fostering real-time collaboration and empowering teams to react swiftly and cohesively in disaster situations.

To address the critical need for accurate and trustworthy information during crises, the system will incorporate real-time validation mechanisms. These will evaluate the credibility of data from nontraditional sources, such as social media and IoT devices, ensuring that actionable intelligence is both reliable and timely. Leveraging machine learning techniques, the system will adapt to evolving data patterns, refining its validation algorithms to meet the dynamic demands of emergency response environments. Hybrid machine learning models, combining supervised and unsupervised methods, are recommended to enhance the robustness of data validation processes and maintain reliability under varying conditions.

At the core of the framework, predictive analytics models will play a vital role in identifying patterns and forecasting the evolution of incidents, thereby empowering decision support systems. These systems will enable emergency response teams to anticipate critical developments and allocate resources proactively, enhancing situational awareness. By integrating machine learning algorithms tailored to disaster scenarios, the system will provide responders with tailored insights that simplify complex decision-making processes. To ensure the effectiveness of these tools, maintaining interpretability through clear visualizations and actionable recommendations is essential, as it prevents information overload for decision-makers.

A user-centric design will further strengthen the system's utility, offering customizable interfaces that allow first responders to dynamically prioritize information during high-pressure situations. This feature will enhance situational awareness and operational effectiveness, reducing cognitive load and supporting better decision-making in disaster scenarios. Including real-time heatmaps and dashboards that display critical metrics is highly recommended, enabling responders to focus on the most urgent aspects of the situation.

Stakeholder engagement will be a cornerstone of the framework's development, ensuring that the system aligns with the operational realities and needs of diverse user groups, including emergency responders, policymakers, and community leaders. By actively involving stakeholders throughout the design and implementation process, the project will foster a sense of ownership, encourage feedback-driven iterations, and ensure practical applicability. Furthermore, collaboration with these groups will help refine user interfaces, data visualization tools, and operational protocols, guaranteeing

that the final system integrates seamlessly into existing workflows and maximizes its impact in real-world scenarios.

The framework will undergo iterative testing in both simulated and real-world disaster scenarios to assess its impact on disaster management and public safety innovation. By addressing the technological and operational gaps identified in the literature and by organizations like IFAFRI, the project will deliver a reliable, adaptable, and predictive decision-support tool that redefines how emergency teams interact with complex data environments. Establishing partnerships with international organizations will help benchmark the system's effectiveness and scalability, ensuring its global applicability and impact. These advancements align with the mission of the Digital Systems Department of University X to drive public safety innovation and develop cutting-edge computational solutions with tangible societal benefits.

Supplementary Material 3-3: Keyword by GPT

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Please structure the recommendation using the keywords provided below:

- Predictive Analytics
- Decision Support Systems
- Data Integration
- Emergency Response
- Real-Time Validation
- Heterogeneous Data Sources
- Machine Learning
- Disaster Management
- Public Safety Innovation

Output

To approach the research outlined in the proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration," the student must adopt an integrated strategy that weaves multiple core components—predictive analytics, decision support systems, real-time validation, and data integration—into a unified framework. The study should be grounded in a thorough literature review of existing gaps, particularly those highlighted by both academic sources and practical guidelines (such as those from the International Forum to Advance First Responder Innovation). In doing so, the student will ensure that each element, from heterogeneous data handling to disaster management protocols, is systematically addressed rather than approached as a series of disconnected tasks.

A key initial step involves establishing robust mechanisms for data ingestion and standardization that draw on machine learning and semantic techniques to handle both environmental sensor feeds and citizen-generated reports. Rather than treating these data types separately, the student should design a single architecture that harmonizes their formats, validates their credibility, and incorporates predictive models for incident evolution. This approach calls for a real-time pipeline that simultaneously ingests raw feeds (e.g., social media updates, infrastructure telemetry), applies quality checks (source reliability, recency, anomaly detection), and prepares data for predictive analytics modules. By framing the data lifecycle as a continuum, the student can maintain coherence across tasks like preprocessing, analysis, and final presentation in decision support interfaces.

In parallel, developing user-centric interfaces should not be an isolated activity. While iterative design cycles and direct consultation with first responders remain crucial, these efforts must explicitly build on insights from data integration and predictive analytics. For instance, if the system detects a spike in social media alerts about flooding in a particular region, the interface should highlight that region proactively, offering real-time situational awareness metrics that reflect both sensor data and predictive outputs. This alignment ensures that each interface element naturally emerges from the system's analytic underpinnings rather than appearing as a bolt-on feature for user convenience.

A cohesive plan for validation under both simulated and real-world conditions is equally vital. Controlled scenarios, where synthetic or partial data is introduced, can test how well the system manages multiple data streams and how accurately it forecasts disaster trajectories. Collaborations with emergency response teams can then validate these findings in actual or near-real conditions—evaluating how effectively first responders can act on alerts, how well the analytics scale during peak data influx, and whether situational awareness truly improves. Critically, rather than grouping results by keywords (such as “predictive analytics success” or “data integration performance”), the student should present a unified evaluation framework that shows how each component (data ingestion, ML-based validation, interface usability) synergizes to accelerate decision-making and boost operational efficiency.

Despite its potential, the research may encounter significant challenges. Data from nontraditional sources, including social media, often exhibits inconsistencies, noise, or gaps; strategies like probabilistic modeling, metadata tagging, and automated filtering should be formulated to maintain data quality. Computational bottlenecks could arise when handling large-scale, real-time feeds, necessitating high-performance cloud resources or distributed computing solutions. Furthermore, first responders may be skeptical about the trustworthiness of alerts derived from machine learning predictions; implementing explainable AI techniques can mitigate these concerns by clarifying how certain conclusions or warnings are generated.

Ultimately, this line of study can profoundly elevate public safety innovation by offering an integrated decision-support tool that unifies predictive analytics, real-time data validation, and user-centric interfaces into a seamless whole. By avoiding the temptation to address each technical concept separately and instead demonstrating how data integration, machine learning, and practical disaster management guidelines interrelate, the student will deliver a coherent, end-to-end solution. This comprehensive framework will underscore the transformative potential of advanced analytics for

emergency response—bridging the gap between theoretical innovation and the tangible needs of those on the front lines of disaster management.

Supplementary Material 3-4: Concepts from topic modeling

Please analyze the following PhD proposal titled “Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration”. Based on the proposal, provide recommendations on how the student should approach the research, including suggested methods, key steps, and potential challenges. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

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Please structure the recommendation using the concept provided below:

- Technology Awareness and Education in Disaster Management
- Disaster Management Interventions Through Autonomous Systems
- Capability and Capacity Building for Digital Resilience
- Digital Technology-Based Monitoring and Prevention of Below-Surface Hazards/Accidents
- Use of Social Media in Crisis Communication
- Data Collection Through Social Media
- Communication Networks and Data Applications in Disasters
- Disaster Management Modeling
- Emergency Response Management Systems

Output

The proposed research on "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration" offers a comprehensive and innovative approach to addressing critical challenges in emergency response management. To ensure the study is conducted effectively, the researcher should adopt a methodologically rigorous and interdisciplinary framework that integrates the specified topics and central themes into a unified narrative. The research should begin by deepening the analysis of existing literature and technological trends in disaster management, particularly focusing on how advancements in autonomous systems, digital resilience, and below-surface hazard prevention can contribute to emergency response systems. This would set a solid theoretical foundation while identifying key technological and operational gaps, including data fragmentation, inconsistent formats, and the absence of reliable real-time validation mechanisms.

The research should approach these challenges systematically by embedding principles of interoperability and user-centric design within the proposed framework. Developing a scalable architecture to harmonize diverse data streams requires leveraging cutting-edge digital technology-based monitoring tools and communication networks that can aggregate, process, and disseminate information from traditional and nontraditional sources. Specifically, the study should investigate how communication networks such

as 5G and Internet of Things (IoT)-enabled devices can enhance the real-time collection and transfer of data in disaster scenarios. These technologies have the potential to significantly reduce latency and improve the accuracy of situational reports, enabling faster and more effective decision-making. Furthermore, the researcher could explore the integration of blockchain technology for secure and traceable data validation, which would ensure the credibility of nontraditional sources, such as citizen-generated reports and social media feeds. For instance, real-time data validation mechanisms could employ machine learning models trained on both structured and unstructured data, ensuring the credibility of inputs from citizen-generated reports and social media. Moreover, integrating social media analytics into disaster management models would not only enhance situational awareness but also enable rapid decision-making by identifying trends and forecasting incident evolution in real time.

The study must incorporate advanced predictive analytics techniques, utilizing simulation-based methodologies to test and refine the system in both controlled and real-world scenarios. This iterative evaluation would allow the researcher to assess how predictive models perform in forecasting hazard progression, optimizing resource allocation, and supporting proactive decision-making. By aligning this evaluation with user-centric principles, the system interfaces could be tailored to first responders' varying levels of technological literacy, enabling dynamic prioritization of critical data and ensuring actionable insights are readily accessible under high-pressure conditions.

To enhance the study's relevance and societal impact, the researcher should address capability and capacity building for digital resilience among first responders. This includes incorporating technology awareness and education programs within the framework to improve the operational readiness of responders when engaging with autonomous systems and complex data environments. Such programs could be developed in collaboration with emergency management training centers to provide hands-on experience with the proposed decision-support system. These training sessions could incorporate scenario-based exercises that simulate real-world emergencies, allowing responders to familiarize themselves with the system's functionalities and providing valuable feedback for iterative improvement. Additionally, the research could propose certification pathways for first responders who demonstrate proficiency in using the system, thereby institutionalizing the adoption of advanced technologies in emergency response operations. Exploring the integration of autonomous systems for monitoring below-surface hazards could significantly augment the system's scope, offering novel interventions in disaster management. Active stakeholder engagement is also crucial, as it ensures the framework reflects the practical needs and operational realities of diverse user groups, including emergency responders, policymakers, and community organizations, thereby enhancing the system's usability and adoption.

By weaving together these elements into a cohesive narrative, the research could redefine emergency response management systems, presenting an adaptable and reliable decision-support tool that enhances operational efficiency and public safety. The proposed framework's emphasis on predictive analytics, real-time validation, and interoperable design ensures its alignment with the mission of the Digital Systems Department of University X, promising meaningful contributions to disaster management innovation and the broader field of public safety technology.

Supplementary Material 4: ChatGPT prompts for the secondary analysis

Supplementary Material 4-1: Geospatial Intelligence and Remote Sensing

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To strengthen the foundation of the proposed framework for disaster risk management, Geospatial Intelligence and Remote Sensing should be established as a central pillar. This pathway is justified by the critical need for first responders to anticipate incident evolution and take proactive measures, especially in rapidly changing and high-pressure scenarios. Current systems often fail to provide forward-looking insights, limiting their ability to optimize resource allocation and minimize disaster impacts. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

Output

The proposed PhD research provides a robust framework for addressing critical gaps in decision-making systems for first responders, integrating predictive analytics and advanced data harmonization techniques to improve situational awareness and decision-making speed. To further enhance the research, it is imperative to incorporate geospatial intelligence and remote sensing as foundational components of the proposed framework. This integration will allow the system to account for spatial and temporal dynamics that are vital for anticipating incident evolution, optimizing resource allocation, and mitigating disaster impacts.

Establishing a geo-data preprocessing pipeline is essential to address inconsistencies in spatial resolutions and coordinate systems across diverse data sources such as satellite imagery, drone footage, and sensor networks. This pipeline should include methods for normalizing spatial data and ensuring compatibility with predictive analytics models. Additionally, the development of a multi-resolution fusion technique is recommended to combine wide-coverage, lower-resolution data with high-resolution, localized feeds. This approach would significantly improve the system’s ability to detect hazards with precision while maintaining broader situational awareness.

To tailor the system's outputs to the unique characteristics of each disaster scenario, spatial analysis methods, such as GIS-based tools and network analysis, should be employed. These methods would enable the identification of hazard zones, evacuation routes, and resource allocation needs in real time. The incorporation of these spatial insights will ensure that first responders can adapt their strategies dynamically to the geographic context of an incident, whether urban, rural, coastal, or mountainous. Validating these models in diverse geographic and environmental conditions is critical to ensuring their reliability and adaptability. By conducting iterative testing in varied contexts, the research can account for the unique challenges posed by different disaster types and locations.

Furthermore, the inclusion of resource allocation logic within the predictive framework will translate the system's outputs into actionable strategies on the ground. This aspect should prioritize usability and effectiveness, measuring success through real-world collaborations and metrics such as first responders' satisfaction and operational efficiency. Engaging first responders throughout the development process will also ensure that the system's interfaces and outputs align with their needs and expectations.

By integrating geospatial intelligence and remote sensing into the decision-support framework, this research can extend its impact, providing first responders with a sophisticated, proactive tool that dynamically adapts to complex and evolving emergency scenarios. This approach not only aligns with the broader objectives of enhancing public safety and disaster management but also reinforces the societal relevance of computational innovations developed at the Digital Systems Department of University X.

Supplementary Material 4-2: Digital Twin technology

Please analyze the following PhD proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration". Based on the proposal, provide recommendations on how the student should approach the research, including suggested methods, key steps, and potential challenges. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

Proposal: "This research proposal, titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration," is conducted at the Digital Systems Department of University X. The PhD aims to address the critical challenges faced by first responders in rapidly evolving emergency scenarios by developing a decision-support framework that integrates diverse data sources, validates their reliability, and leverages predictive analytics to provide actionable insights.

A preliminary literature review revealed substantial gaps in the current systems designed to support first responders during emergencies. Despite the availability of extensive data from both traditional sources, such as environmental sensors and infrastructure feeds, and nontraditional sources, including social media and citizen-generated reports, existing systems fail to seamlessly integrate these heterogeneous streams. This fragmentation complicates situational awareness and slows down critical

decision-making processes. The review also identified a lack of mechanisms to validate nontraditional data, further diminishing the reliability of the information available to responders.

These findings align with the analysis conducted by the International Forum to Advance First Responder Innovation (IFAFRI), particularly Capability Gap 4. This analysis underscores the difficulty of incorporating information from diverse and nontraditional sources into incident command operations. Key challenges identified include inconsistent data formats, the absence of real-time validation mechanisms, and a lack of adaptable interfaces that allow responders to prioritize and customize information according to situational needs.

Motivated by these challenges, this research seeks to design, develop, and evaluate a novel framework that integrates predictive analytics and advanced data harmonization techniques. The proposed system will focus on three key objectives. First, it will establish a scalable architecture to integrate heterogeneous data sources, ensuring compatibility across diverse formats and enabling seamless communication among disparate systems. Second, the framework will incorporate real-time data validation mechanisms to assess the credibility of information from nontraditional sources. Finally, predictive analytics models will be employed to identify patterns, forecast incident evolution, and support proactive decision-making.

The methodology will involve designing a user-centric system that provides first responders with customizable interfaces, enabling them to prioritize information dynamically during high-pressure situations. By combining machine learning techniques with advanced data processing, the system will deliver tailored insights that enhance situational awareness. The framework will be evaluated through iterative testing in simulated and real-world disaster scenarios to assess its effectiveness in improving decision-making speed and accuracy.

This research represents a significant step toward addressing the technological and operational gaps identified in the literature and by organizations like IFAFRI. By providing first responders with a reliable, adaptable, and predictive decision-support tool, the project aims to redefine how emergency response teams interact with complex data environments. The outcomes of this research will not only enhance the effectiveness of disaster management operations but also contribute to the broader field of public safety innovation, aligning with the mission of the Digital Systems Department of University X to develop cutting-edge computational solutions with tangible societal impacts.”

To strengthen the foundation of the proposed framework for disaster risk management, Digital Twin technology should be established as a central pillar. This approach is justified by its ability to create real-time, interactive simulations that mirror complex disaster scenarios. These virtual replicas provide first responders with a dynamic environment to monitor, predict, and experiment with potential response strategies during emergencies. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

Output

The PhD proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration" provides a strong foundation by addressing the technological and operational gaps in emergency response systems. To further enrich the research and maximize its potential societal impact, the proposed framework should incorporate Digital Twin technology as a pivotal component. This integration will allow the creation of real-time, interactive simulations that mirror the complexities of disaster scenarios, offering a dynamic environment for testing, monitoring, and refining response strategies. The establishment of a layered architecture will be essential, wherein data ingestion from diverse sources, such as sensors and IoT devices, operates independently of simulation modules like 3D visualization and situational modeling. This separation will ensure that the system remains scalable and capable of real-time updates, an essential feature for high-stakes decision-making environments.

Moreover, the incorporation of dynamic hazard modeling will significantly enhance the system's ability to adapt to evolving conditions. For instance, the virtual environment should adjust in response to new data inputs, such as rising flood levels or expanding fire perimeters, validated against historical incident data to confirm accuracy and realism. Cross-layer calibration must also be prioritized, comparing simulated conditions with real-world logs or sensor data to identify and alert users to major discrepancies. This feature not only strengthens the reliability of the system but also instills confidence among its users. Additionally, the framework should include scenario-based training modules, enabling first responders to test various strategies, such as evacuation routes and resource deployment, while receiving instant feedback on their outcomes. This capability will serve as a critical tool for building readiness and improving tactical decision-making under pressure.

Collaboration with emergency management partners will be indispensable in refining the system. Field tests in realistic settings should be conducted to assess both technical performance and usability, with particular attention given to the design of user interfaces. Interfaces must align with the high-pressure workflows of first responders, minimizing resistance to adoption by ensuring that the system is intuitive and seamlessly integrates into existing protocols. By focusing on these enhancements, the research will not only address identified gaps in the literature and industry standards but also contribute to a transformative approach in disaster risk management. The outcomes will bridge the divide between theoretical advancements and practical applications, thereby reinforcing the role of the Digital Systems Department at University X as a leader in the development of impactful, innovative solutions for public safety challenges.

Supplementary Material 4-3: Semantic Web Technologies

Please analyze the following PhD proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration". Based on the proposal, provide recommendations on how the student should approach the research, including suggested methods, key steps, and potential challenges. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

Proposal: "This research proposal, titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration," is

conducted at the Digital Systems Department of University X. The PhD aims to address the critical challenges faced by first responders in rapidly evolving emergency scenarios by developing a decision-support framework that integrates diverse data sources, validates their reliability, and leverages predictive analytics to provide actionable insights.

A preliminary literature review revealed substantial gaps in the current systems designed to support first responders during emergencies. Despite the availability of extensive data from both traditional sources, such as environmental sensors and infrastructure feeds, and nontraditional sources, including social media and citizen-generated reports, existing systems fail to seamlessly integrate these heterogeneous streams. This fragmentation complicates situational awareness and slows down critical decision-making processes. The review also identified a lack of mechanisms to validate nontraditional data, further diminishing the reliability of the information available to responders.

These findings align with the analysis conducted by the International Forum to Advance First Responder Innovation (IFAFRI), particularly Capability Gap 4. This analysis underscores the difficulty of incorporating information from diverse and nontraditional sources into incident command operations. Key challenges identified include inconsistent data formats, the absence of real-time validation mechanisms, and a lack of adaptable interfaces that allow responders to prioritize and customize information according to situational needs.

Motivated by these challenges, this research seeks to design, develop, and evaluate a novel framework that integrates predictive analytics and advanced data harmonization techniques. The proposed system will focus on three key objectives. First, it will establish a scalable architecture to integrate heterogeneous data sources, ensuring compatibility across diverse formats and enabling seamless communication among disparate systems. Second, the framework will incorporate real-time data validation mechanisms to assess the credibility of information from nontraditional sources. Finally, predictive analytics models will be employed to identify patterns, forecast incident evolution, and support proactive decision-making.

The methodology will involve designing a user-centric system that provides first responders with customizable interfaces, enabling them to prioritize information dynamically during high-pressure situations. By combining machine learning techniques with advanced data processing, the system will deliver tailored insights that enhance situational awareness. The framework will be evaluated through iterative testing in simulated and real-world disaster scenarios to assess its effectiveness in improving decision-making speed and accuracy.

This research represents a significant step toward addressing the technological and operational gaps identified in the literature and by organizations like IFAFRI. By providing first responders with a reliable, adaptable, and predictive decision-support tool, the project aims to redefine how emergency response teams interact with complex data environments. The outcomes of this research will not only enhance the effectiveness of disaster management operations but also contribute to the broader field of public safety innovation, aligning with the mission of the Digital Systems Department

of University X to develop cutting-edge computational solutions with tangible societal impacts.”

To strengthen the foundation of the proposed framework for disaster risk management, Semantic Web Technologies should be established as a central pillar. The rationale lies in the fragmented nature of the data sources that first responders must handle, including traditional sources like environmental sensors and nontraditional ones such as social media and citizen-generated reports. These sources often use inconsistent formats and terminologies, complicating interoperability and real-time integration. Please do not use bullet points, numbered lists, or headings, but instead provide a continuous paragraph in a formal academic tone with full sentences throughout.

Output

The research proposal titled "Enhancing Decision-Making Systems for First Responders through Predictive Analytics and Advanced Data Integration" presents a compelling framework aimed at addressing critical gaps in emergency response systems. To strengthen the proposed approach and ensure the success of this ambitious initiative, the integration of Semantic Web Technologies should be considered a foundational element. These technologies are particularly well-suited to resolving the inherent challenges associated with the fragmented and heterogeneous nature of the data sources utilized by first responders. Traditional sources such as environmental sensors and infrastructure feeds, alongside nontraditional inputs like social media or citizen-generated reports, often present data in inconsistent formats with varying terminologies, hindering interoperability and real-time analysis. Semantic Web Technologies, by enabling standardized representations and linked data frameworks, can ensure seamless communication and data integration across diverse systems.

In line with this, the development of a robust ontology or the adaptation of an existing one tailored to disaster management should be prioritized. This ontology would formalize key disaster-related concepts, their relationships, and context-specific attributes, serving as a unified schema for integrating and querying data. In addition, a modular ontology engineering approach should be employed to facilitate scalability and adaptability, allowing the framework to accommodate evolving disaster management needs. Adhering to international standards for data exchange and semantic representation, such as those from the W3C, will ensure alignment with global best practices and improve interoperability. Utilizing an RDF triplestore for storage and query processing would enable efficient management of complex and interconnected datasets.

Real-time data validation mechanisms, leveraging machine learning classifiers, should also be implemented to address issues of credibility and reliability. These classifiers can assess incoming information for credibility scoring and detect anomalies in sensor feeds, ensuring that only high-quality and actionable data informs decision-making processes. Moreover, predictive analytics could complement these Semantic Web approaches by using validated data streams to forecast incident evolution, enabling responders to anticipate challenges and optimize resource allocation.

To ensure the practical applicability of the framework, an iterative testing approach should be employed. This should begin with structured data from traditional sensor feeds, allowing the foundational architecture and predictive models to be refined before incorporating less structured and more volatile inputs such as social media or crowdsourced data. Testing scenarios should increase in complexity, simulating the dynamic and unpredictable conditions typical of real-world emergencies. Equally critical is the involvement of first responders throughout the user-centered design process. This engagement will ensure that the interfaces developed are intuitive, adaptable, and aligned with the operational realities of emergency response. Features enabling responders to dynamically prioritize and customize information based on situational needs should be a key focus, as such flexibility can significantly enhance the system's usability under high-pressure conditions.

Stakeholder engagement must extend beyond first responders to include policymakers, technology developers, and community representatives, fostering a participatory approach to the framework's development. Policymakers can provide strategic guidance on regulatory and ethical considerations, ensuring that the system adheres to legal standards and public safety mandates. Technology developers can collaborate to integrate the latest advancements, enhancing the system's functionality and robustness. Community representatives can offer insights into the social dynamics and contextual factors that shape emergency scenarios, enabling a more holistic and inclusive design. Regular workshops, focus groups, and co-creation sessions with these stakeholders will ensure the framework aligns with diverse needs and expectations, fostering a sense of shared ownership and trust.

Finally, comprehensive performance evaluations must be conducted to assess the system's impact on situational awareness and decision-making speed. Controlled simulations should measure improvements in key metrics, followed by trials in real-world disaster scenarios to validate the system's efficacy in operational environments. These evaluations will provide critical insights into the framework's strengths and areas for enhancement, guiding further development. By combining advanced data integration, machine learning, and Semantic Web Technologies, this research has the potential to deliver transformative benefits to emergency response operations, setting a benchmark for innovation in public safety and disaster risk management.