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Enhancing Forest Fire Response through Integrated Real-Time Data and Decision-Support Analytics

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Abstract. *This study presents a real-time monitoring system to support wildfire management in the Caatinga biome, Brazil. The system integrates IoT sensor data, satellite imagery, and climate APIs, providing updated and centralized information to firefighting teams. Based on Systems Theory, it offers advanced tools for tracking, weather forecasting, and strategic planning, enhancing fire response. Implemented in a regional brigade, the system was evaluated using quantitative and qualitative metrics, showing improvements in situational awareness and resource management. Experimental results indicate an average system response time below 2 minutes, hourly data refresh cycles, and fire location accuracy close to 92%, demonstrating the operational reliability of the proposed solution. The solution strengthens prevention and firefighting efforts, optimizing resources and enhancing emergency actions in the semi-arid region.*

Keywords. *Forest Fire, Mobile Application; Business Intelligence; Decision-Support Systems; Real-Time Monitoring*

Resumo. *Este estudo apresenta um sistema de monitoramento em tempo real voltado ao combate de incêndios no bioma brasileiro da Caatinga. A solução integra dados de sensores IoT, imagens de satélite e APIs de clima, oferecendo informações centralizadas às equipes de resposta. Baseado na Teoria dos Sistemas, o serviço fornece ferramentas para rastreamento, previsão do tempo e planejamento estratégico. Implementado em uma brigada regional, o sistema foi avaliado por métricas quantitativas e qualitativas, demonstrando*

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avanços na consciência situacional e na gestão de recursos. Os resultados experimentais indicam um tempo médio de resposta do sistema inferior a 2 minutos, ciclos de atualização de dados a cada hora e acurácia na localização de focos de incêndio próxima de 92%, demonstrando a confiabilidade operacional da solução proposta. Em síntese, o sistema contribui para otimizar ações de prevenção e combate, fortalecendo a resposta a emergências na região semiárida.

Palavras-Chave. *Incêndios Florestais; Aplicação Móvel; Inteligência de Negócios; Sistemas de Apoio à Decisão; Monitoramento em Tempo Real.*

1. Introduction

According to data from the Fire Program (*Programa de Queimadas*[1]) of the National Institute of Space Research (*Instituto Nacional de Pesquisas Espaciais*, INPE), the number of fires in Brazil in January and February 2024 almost doubled compared to the same period in 2023. Furthermore, the number of fire outbreaks in Brazil has surpassed 200,000 occurrences in 2022 and 189,000 occurrences in 2023. Considering the data of 2023, 12% of these fire outbreaks are in the Caatinga biome, which covers around 11% of the Brazilian territory. In Brazil, using fire to clear land for agriculture remains the most cost-effective method compared to investing in equipment and labor [Silva Junior and Pacheco 2021]. Firefighting in vegetation areas is complex, requiring skilled planning, coordination, large teams, and diverse resources. Specifically, firefighting in vegetation areas presents significant challenges and complexities, requiring technique, expertise, and careful planning from the firefighters involved. Moreover, forest fires are commonly scenarios that demand dozens of firefighters and different types of fire-suppression resources. Therefore, firefighting in dry forests presents additional challenges, such as recognizing the affected area (including the presence of water sources, terrain features, and nearby access roads), strategic planning, and the deployment of staff and equipment (vehicles, trucks, and fire-suppression tools) [Komalapati et al. 2021, de Souza et al. 2022].

Wildfires cause not only severe environmental impacts but also substantial economic losses for affected regions [Reddy et al. 2019]. Several factors contribute to vegetation fires [Silva Junior and Pacheco 2021], including consistently warmer and drier climates, particularly in Northeast Brazil, associated with climate change and deforestation. However, intentional burning for land clearing remains widespread, mainly driven by agricultural expansion and livestock activities.

To the best of our knowledge, most fire brigades in Brazil lack software to support firefighters, despite living in a technological society. This reinforces the need for technological solutions to aid decision-making in a fast and efficient manner [Çolak and Sunar 2020, de Souza et al. 2022, Araújo et al. 2025]. This work extends the previous work [Araújo et al. 2025], moving beyond a primarily operational real-time monitoring system toward a more comprehensive and analytically grounded decision-support platform. While the earlier study introduced the core architecture for real-time

[1]https://terrabrasilis.dpi.inpe.br/queimadas/portal/

wildfire detection and visualization, the present work advances the system in several key dimensions. First, it incorporates a multi-source fire hotspot integration strategy combining FIRMS and BDQueimadas, improving detection reliability and temporal consistency. Second, it introduces an unsupervised clustering approach for hotspot aggregation, reducing spatial redundancy and enhancing situational awareness. Third, the system architecture has been expanded to support fire brigades through notification services and a tighter integration with institutional emergency coordination workflows. Finally, this study provides a more robust empirical evaluation, including quantitative performance metrics and qualitative feedback from operational users, thereby strengthening both the methodological rigor and the practical relevance of the proposed solution within the Information Systems domain. Therefore, this work proposes the development of a whole decision-support service that aggregates data from various sources and presents it clearly to fire brigades, aiming to enhance strategic planning and assist in operational tasks.

The general objective is to develop an integrated real-time burn monitoring system to help firefighters in Brazil detect, analyze, and respond to fires, ensuring efficient resource management and improving decision-making in firefighting operations. The specific objectives include implementing a real-time data collection platform that integrates Internet of Things (IoT) sensors, satellite imagery, and weather APIs to monitor and detect fires. The interface will support continuous monitoring of fire conditions for quick, coordinated responses. Additionally, a Business Intelligence (BI) system will enhance decision-making by providing interactive dashboards and analytical reports, allowing firefighting teams to visualize key information such as fire growth, temperature, precipitation, intensity, and response occurrences.

From an Information Systems perspective, the proposed solution is grounded in a sociotechnical view in which technology, organizational processes, and human actors interact to support complex decision-making scenarios. By integrating heterogeneous data sources into a unified and operational information flow, the proposed approach aligns with established principles of Decision-Support Systems, enabling timely, informed, and context-aware actions in critical wildfire management situations. Its scalable architecture adapts to various biomes and regions, considering local characteristics. This flexibility makes the system globally applicable, enhancing its impact. Additionally, its robust technological infrastructure transforms traditional firefighting into more intelligent and coordinated operations, advancing disaster management and improving safety, efficiency, and environmental protection.

The remainder of this application paper is structured as follows. Section 2 provides the problem setting and the necessary background information. The proposed workflow is detailed in Section 3. Section 4 and 5 present the practical deployment and the main results achieved by the proposed service and the related discussions. Section 6 discusses the related work, while conclusions and future directions are presented in Section 7.

2. Background

The increasing frequency and severity of forest fires highlight the need for innovative firefighting and prevention strategies. This study explores the role of technology, particularly

Software as a Service (SaaS), in enhancing firefighting capabilities and mitigating risks. SaaS is a cloud-based software delivery model in which the software is hosted off-premise and delivered via the web [Ghouri and Mani 2019]. This approach enables organizations to reduce infrastructure management burdens and focus on their core activities. As a result, SaaS is increasingly adopted across various applications, including disaster management [Ibrahim et al. 2023]. This work proposes a decision-support service leveraging SaaS to address challenges, enhance fire response, and protect ecosystems and communities.

Regarding firefighting and prevention, SaaS holds significant potential to enhance operational efficiency, decision-making processes, and resource management [Castro-Basurto et al. 2021, Araújo et al. 2025]. By benefiting from cloud-based solutions, firefighting brigades can overcome traditional limitations associated with on-premise software deployment and data management. In other words, the brigade is not required to manage software operations. Therefore, the adoption of SaaS in this context offers several advantages, as discussed in [Ghouri and Mani 2019, Seifert et al. 2023, Stavrinides and Karatza 2020]. Among them, we can highlight the following: i) Real-time data access: SaaS platforms enable firefighting personnel to access critical information and situational updates in real-time, regardless of their location; ii) Scalability and flexibility: the service can quickly scale usage up or down based on changing operational needs, ensuring satisfactory response times for users even during periods of heavy usage or peak loads; iii) Integration with IoT and sensors: SaaS platforms can integrate with IoT devices and sensor networks deployed in fire-prone areas. By aggregating data from remote sensors, drones, and satellite imagery, the proposed service can provide useful information to firefighting teams, enabling proactive fire detection, monitoring, and response; iv) Collaboration and communication: this kind of service facilitates a continuous collaboration and communication among firefighting teams, monitoring centers, and support staff. Through features such as file (e.g., photos and videos) sharing and task assignment, SaaS streamlines coordination efforts and promotes effective teamwork during firefighting operations; v) Reliability: SaaS systems are consistent and remain available to users within specified time frames. Achieving reliability often requires deploying monitoring and diagnostic tools; vi) Analytics and predictive modeling: SaaS solutions equipped with advanced analytics and predictive modeling capabilities can help firefighting agencies anticipate fire behavior, assess risk levels, and prioritize resource allocation. By analyzing historical data, weather patterns, and terrain characteristics, these platforms enable firefighters to make data-driven decisions that maximize the effectiveness of firefighting efforts and minimize the impact of wildfires on communities and ecosystems.

In summary, SaaS offers a powerful suite of tools and capabilities that can significantly enhance the role of technology in supporting firefighting brigades to combat wildfires, provide effective decision-making, mitigate risks, and protect lives and property in an increasingly dynamic and challenging environment. In this sense, this work addresses the first four advantages previously stated.

In another perspective, research areas such as Remote Sensing and Monitoring, Geographic Information Systems (GIS), IoT, and Business Intelligence present an overlapping of knowledge with the present application. Remote sensing platforms, such as satellites, drones, and aerial reconnaissance systems, aim to detect and monitor disasters and environmental anomalies early [Arab et al. 2022]. These platforms provide real-time data (e.g., fire spread, flooding, deforested areas, and hotspots) to identify and prioritize areas for intervention. Work such [Si Salah et al. 2019] highlights the benefits of remote sensing platforms over different kinds of environmental anomalies. Regarding GIS applications, [Subburaj et al. 2024, Rahaman and Esraz-Ul-Zannat 2021] integrates spatial data from multiple sources to create detailed maps and spatial models to support visualization and decision-making. In this sense, GIS is useful to support firefighters in visualizing fire perimeters, evacuation routes, and critical infrastructure, facilitating informed decision-making and effective coordination.

IoT devices and sensor networks are a fundamental source of information since they collect real-time data on environmental conditions, such as temperature, humidity, and wind speed [de Oliveira et al. 2025]. These sensors provide valuable insights, which allies with remote sensing platforms and GIS can support timely decision-making and response efforts, as discussed in [Ejaz et al. 2019, Shah et al. 2019]. Concerning BI, its principles can support the information and insights in the proposed decision-support service by leveraging data-driven technologies and analytical tools to process, analyze, and visualize important information. For instance, in [Milanés-Batista et al. 2020], the authors propose the application of techniques and tools of BI to expose the patterns of vulnerability and risk in Cuba, taking into account useful information regarding the occurrence of meteorological extreme events in vulnerable territories. In this paper, we will explore the integration of Remote Sensing and Monitoring, GIS, IoT, and BI in enhancing the functionality and effectiveness of the proposed decision-support service.

Another essential tool in this context is Machine Learning (ML), which enables the analysis and interpretation of large volumes of data generated from various sources. ML approaches become useful in applications aimed at combating forest fires, allowing the identification of patterns, prediction of occurrences, and optimization of response strategies, significantly contributing to the mitigation of their impacts. In [Jain et al. 2020], the authors analyze the main ML approaches employed in combating forest fires, categorizing them into supervised algorithms, unsupervised algorithms, and agent-based methods, highlighting their respective applications and contributions in this context. Unsupervised algorithms aim to identify patterns and extract useful information from data where the target variable is not previously defined. These algorithms offer different approaches to data organization and analysis, enabling the identification of underlying structures in unlabeled datasets. In this study, unsupervised learning algorithms were applied to cluster fire hotspots, supporting users to better interpret maps by reducing the visual clutter caused by a high concentration of fire spots in the same area.

3. A Decision-support Service for Firefighting in Dry Tropical Forest

Caatinga is the most important biome for livestock in the Brazilian semi-arid region [de Souza et al. 2022, Silva Junior and Pacheco 2021]. To this end, an important ally for this preserving task can be the application of technological resources, such as the decision-support service[2] proposed in this work. To the best of our knowledge, this project pro-

[2]Due to intellectual property restrictions, contact the authors by email to access the repository.

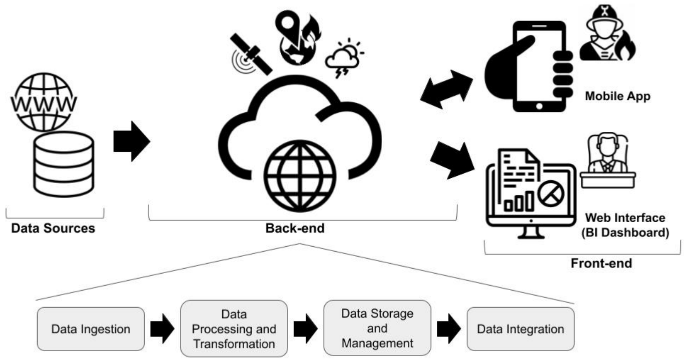

Figure 1. The project architecture of the proposed application.

poses the first decision-support service able to provide different useful information (location, weather conditions, video/image storage, fire outbreaks management, and tracks to fire outbreaks) to the Brazilian fire brigades in only one application. In this sense, this section presents the architecture of the proposed decision-support service, focusing on the internal components and data management mechanisms. The decision-support tool is designed to address the complex challenges of collecting, processing, and managing data from heterogeneous sources in real-time. By dealing with large-scale, multi-source environmental data, this application aims to provide comprehensive support for firefighting efforts in the Caatinga biome.

3.1. Architecture Overview

The architecture of the proposed decision-support tool is modular, and divided into three primary components (as illustrated in Figure 1): Data Sources, Back-end, and Front-end. This modularity supports scalability, flexibility, and efficient real-time data processing, making it well-suited for the data-intensive operations involved in firefighting.

Data Sources include various external streams from the web, such as online weather services (Weather API)[3], satellite data from *FIRMS* (Fire Information for Resource Management System)[4] and DB Queimadas[5], and geospatial data from OpenStreetMap[6] (OSM). Additionally, data generated by users such as images, videos, and manual fire outbreak reports, is collected through the mobile application. The diversity of these data sources presents integration challenges, as each source provides data in different formats, frequencies, and levels of detail. To address these challenges, a robust data processing pipeline has been implemented within the back-end to standardize and merge these diverse datasets.

The Back-end serves as the core processing unit of the decision-support tool, responsible for managing data extraction, transformation, storage, and delivery to the front-end. This component consists of several internal modules designed to manage the com-

[3]https://www.weatherapi.com/
[4]https://firms.modaps.eosdis.nasa.gov/
[5]https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/
[6]https://www.openstreetmap.org/

plex data requirements of the proposed service. The Data Ingestion Module facilitates the extraction of data from external APIs (e.g., Weather API, *FIRMS*) and internal sources (user-generated data) through a unified API interface. It uses asynchronous communication to collect real-time data efficiently, reducing latency and ensuring timely updates for users. This approach enables the decision-support tool to handle multiple data streams simultaneously, mitigating bottlenecks in real-time data collection.

The Data Processing and Transformation Module is crucial for converting raw data into a consistent format suitable for storage and analysis. In this module, the system standardizes, cleans, and integrates the collected data. The data cleaning process employs a rule-based approach, discarding unreliable or inconsistent entries, such as temperature readings that exceed natural limits or show discrepancies compared to existing records in the database. For instance, temperature values that fall outside the expected natural range are flagged and removed. Duplicate fire records are identified using geospatial comparison to avoid redundancy, ensuring data integrity and reliability.

Data storage and management are implemented using the Realtime Database, a NoSQL cloud-based solution chosen for its ability to handle dynamic and unstructured data in real time. Unlike traditional relational models, the Realtime Database employs a hierarchical JSON data structure that enables flexible representation of heterogeneous information such as satellite imagery metadata, weather observations, user reports, and incident records. This design supports efficient synchronization and instantaneous data propagation across clients, ensuring that updates performed by mobile or web applications are immediately reflected across all connected users. The database's scalability and low-latency querying capabilities make it particularly suitable for emergency-response contexts, where rapid access to specific subsets of data (such as active fire locations, environmental indicators, or media evidence) is critical for timely decision-making.

The Data Integration Layer merges heterogeneous data sources into a unified dataset. This layer employs spatial indexing to correlate weather data with fire locations and time-based filtering to ensure that only relevant and recent data is considered. By linking data points based on spatial (geolocation) and temporal (timestamps) parameters, the system provides a comprehensive situational overview, supporting informed decision-making in firefighting efforts.

The Front-end consists of a mobile application and a web-based interface, designed to cater to the needs of both firefighters and managers. The Mobile Application provides firefighters with real-time access to fire data, weather conditions, and navigation routes. Built using React Native, it communicates with the back-end through RESTful APIs to fetch and update data. This bidirectional interaction allows firefighters to manually add new fire reports, share tracks, and manage images and videos associated with specific fires. The application thus enables field personnel to assess environmental conditions quickly, supporting on-the-ground decision-making.

The Web Interface (BI Dashboard) is designed for managers and government stakeholders, offering dashboards that present analytical reports, heat maps, and temporal graphs. The interface, developed using Next.js, leverages BI principles to support strategic decision-making by providing insights into historical trends, resource allocation, and risk assessment. It translates the unified dataset from the back-end into intuitive reports, allowing managers to evaluate fire patterns, allocate resources more effectively, and implement preventive measures.

3.2. Data Management and Processing: Extract, Transform, and Load

Data management in the decision-support tool addresses the challenges faced by real-time data collection and large-scale data handling. The back-end employs several strategies to ensure data quality and efficiency. In this sense, the implementation of the decision-support service relies on a robust ETL (Extract, Transform, Load) process. This process integrates data from various sources, ensures its quality, and stores it in a NoSQL database, providing reliable and real-time information to firefighters and managers. The following subsections describe each phase of the ETL process in detail.

3.2.1. Data Extraction

In the extraction phase, the system collects data from multiple sources, including weather information, fire data, and geospatial details. Data Extraction utilizes a unified API interface that facilitates seamless integration with diverse data sources. By supporting parallel data collection, the decision-support tool can handle large data volumes efficiently and mitigate potential bottlenecks in real-time scenarios. The asynchronous nature of data collection ensures minimal latency and timely updates for end-users.

Weather Data: the system extracts real-time weather information using external APIs such as the Weather API. This data includes key parameters like temperature, humidity, wind speed, and precipitation forecasts for both the current user location and fire outbreak sites identified by *FIRMS*. These weather parameters are critical for evaluating fire risk and planning firefighting strategies.

Fire Data: fire information is extracted using the *FIRMS* API, which provides global fire data based on satellite imagery. The extracted data includes the geolocation (latitude and longitude) of the fire, detection timestamps, and fire brightness levels, where higher brightness indicates more intense fire outbreaks. These data are essential for identifying fire hotspots, assessing their severity, and tracking their development in real-time. In addition to *FIRMS*, fire information is also obtained from the *Banco de Dados de Queimadas* (BDQueimadas), maintained by the Brazilian National Institute for Space Research (INPE). This database compiles fire reports across Brazil, generated from multiple satellite sources and consolidated by the INPE's fire monitoring program. The BDQueimadas system provides continuous near real-time updates, producing new hotspot reports approximately every ten minutes. The extracted data include geolocation, acquisition timestamps, satellite sensor, and confidence level for each fire detection. To ensure temporal alignment, the system synchronizes the BDQueimadas retrieval process with the *FIRMS* API requests, allowing both sources to be queried simultaneously within the same observation window. Although both datasets operate independently, BDQueimadas serves as an authoritative reference for identifying fire hotspots officially recognized by the national monitoring agency, ensuring credibility, spatial accuracy, and consistency within the integrated fire monitoring framework.

Geospatial Data: the system also extracts geospatial data from OpenStreetMap, a collaborative project that offers free geographic information and maps. This data provides valuable insights into the surrounding terrain, including nearby roads, water sources, and natural parks, which aid in navigation and operational planning during firefighting activities. Integrating this data into the system allows for better spatial contextualization of detected hotspots and optimizes the logistical planning of field teams, facilitating access to safe routes, supply points, and high-risk areas. This makes it possible to improve operational decision-making, reduce response time, and increase the efficiency of monitoring and mitigating forest fires.

3.2.2. Data Transformation

Once extracted, the data undergoes a transformation process to ensure quality, consistency, and usability.

Data Standardization: the extracted data from various sources is standardized into a unified format. For instance, geospatial coordinates are converted to a consistent representation, and weather data units are standardized to ensure uniformity. This step is crucial for integrating data from different origins into a cohesive dataset.

Data Cleaning: in this step, the system removes invalid, duplicate, or irrelevant data entries to enhance the accuracy and reliability of the information provided to users. The data cleaning process includes discarding records that are deemed unreliable or show significant discrepancies compared to existing data in the database. For instance, duplicate fire records are identified and removed to prevent redundancy. Similarly, weather data points, such as temperature readings that fall outside the expected range or are impossible to reach under natural conditions, are filtered out. This approach ensures that only consistent and trustworthy data is retained for further processing and analysis, improving the quality of information to support decision-making in firefighting efforts.

Data Integration: the integration process consolidates fire hotspot data from multiple sources, primarily the *FIRMS* (NASA) and *BDQueimadas* (INPE) systems, ensuring temporal and spatial alignment across both datasets. Records are synchronized and merged into a unified structure based on spatial proximity and acquisition time, allowing coincident detections to be aggregated and validated. Spatial indexing techniques are used to correlate fire data with complementary environmental information, such as weather indicators and regional boundaries, while temporal filtering guarantees that only recent and relevant observations are included. The resulting integrated dataset combines satellite-derived fire detections, meteorological data, and user-generated inputs into a single, coherent repository that supports both the mobile and web applications. This approach provides users with a holistic and continuously updated view of the current fire situation, strengthening the reliability and completeness of the system's real-time monitoring and decision-support capabilities.

3.2.3. Data Loading

In the final phase, the transformed data is loaded into the decision-support tool database to be accessed by the user interfaces.

Database: our approach applies Realtime Database, a flexible and scalable NoSQL database designed for managing large volumes of varied and real-time data. This choice of database supports the storage of key information such as fire geolocations, timestamps, brightness levels, weather conditions, and user-generated data (e.g., photos, videos, tracks).

Data Accessibility: the stored data is then made accessible to the front-end components, including the mobile application used by firefighters and the web-based BI interface for managers. The mobile application provides real-time data visualization and enables field personnel to interact with the information, such as registering new fire outbreaks and updating their status. The BI interface leverages this data to generate reports, identify fire patterns, and assist in resource allocation and strategic planning.

The ETL process has a fundamental role in transforming raw, multi-source data into actionable insights, which significantly enhance firefighting efforts. By ensuring that data is consistently extracted, accurately processed, and reliably stored, the decision-support tool provides comprehensive, up-to-date information to its users in their mission to combat wildfires in the Caatinga biome.

3.3. Design Decisions and Technologies

The design of the proposed decision-support tool prioritizes efficiency, scalability, and real-time data processing to address the specific challenges of managing large-scale, heterogeneous data in firefighting scenarios. A key decision in the decision-support tool architecture is the use of asynchronous data collection within the Data Ingestion Module. This approach allows the decision-support tool to handle multiple data streams from diverse sources, such as weather services, satellite imagery, and user inputs, simultaneously. By employing asynchronous communication, the tool significantly reduces latency, ensuring that real-time data is captured and made available to users promptly. This capability is critical for firefighting operations, where delays in data processing can have severe consequences.

For data storage, the decision-support tool applies Realtime Database, a NoSQL database chosen for its flexibility and scalability. The hierarchical data storage model of Realtime Database is particularly suited to represent the complex relationships between various types of data, such as linking weather conditions to specific fire locations or associating media files with individual fire events. Its support for real-time data synchronization allows for immediate updates, which are crucial for maintaining the accuracy and relevance of the information provided to firefighters and managers. Additionally, the choice of Realtime Database facilitates rapid data retrieval, even when dealing with large datasets, enhancing the decision-support tool performance and reliability in data-intensive applications.

The back-end of the proposed tool is implemented using Python and the Flask framework, selected for their versatility and extensive libraries that support various data processing tasks. The robust data processing capabilities of Python make it well-suited for implementing algorithms used in data cleaning, standardization, and integration. For instance, the data cleaning process involves filtering out unreliable data points, such as temperature readings that exceed natural limits, and removing duplicate records using geospatial clustering techniques. The use of Flask as the web framework allows for efficient handling of RESTful API calls between the front-end and back-end, facilitating smooth data exchange and user interaction.

For the front-end, React Native was chosen for the mobile application, while Next.js was selected for the web interface. React Native allows the development of a dynamic, user-friendly mobile application that provides real-time data visualization and supports direct interaction with the back-end. Through this application, firefighters can access up-to-date information on fire locations, weather conditions, and navigational routes, as well as contribute new data, such as reporting new fire outbreaks or uploading media files. Next.js, on the other hand, is used for building the web-based BI dashboard, which offers managers and stakeholders a comprehensive view of historical trends, resource allocation, and risk assessment. This choice of technology enables the creation of an intuitive, responsive interface that can handle complex analytical reports and facilitate strategic decision-making.

Together, these design decisions and technology choices create a robust and flexible tool capable of meeting the demands of real-time data processing, storage, and visualization. The use of asynchronous data collection ensures that the decision-support tool remains responsive and efficient, even when managing multiple data streams. Realtime Database provides a scalable solution for storing the diverse and evolving datasets required for comprehensive fire management. Python and Flask streamline data processing tasks, while React Native and Next.js deliver an engaging and interactive user experience on both mobile and web platforms. This combination of technologies forms the backbone of the decision-support service, enabling it to offer actionable insights and reliable support for firefighting efforts in the Caatinga region.

3.4. Fire Hotspots Clusterization

In this study, unsupervised learning techniques were applied to cluster fire hotspots, addressing challenges associated with interpreting and visualizing fire data. Tools such as *FIRMS* use a spatial threshold of 500 meters in diameter to classify a thermal anomaly as a new fire hotspot. While effective for detecting fires, this approach can result in multiple notifications for closely located hotspots that actually belong to the same large-scale fire. This redundancy can complicate data interpretation and create visual clutter on maps, particularly in scenarios involving extensive or overlapping fire events. To address these challenges, clustering techniques were applied to aggregate closely located fire detections into unified representations of larger fire events. This approach reduces the overrepresentation of fire hotspots on maps, facilitating more accurate data visualization and interpretation for end users. By grouping related detections, clustering not only improves situational awareness but also supports decision-making by providing a clearer and more manageable view of fire activity. This strategy is particularly valuable for firefighting operations, where understanding the scope and spread of individual fires is critical for resource allocation and response planning.

To this end, three algorithms were evaluated for clustering fire hotspots: OPTICS [Ankerst et al. 1999], HDBSCAN [McInnes et al. 2017], and DBSCAN [Khan et al. 2014]. This evaluation aims to identify the most suitable approach for the application context. Then, a total of 6,024 fire hotspots were collected from *FIRMS* within a controlled study area. The generated fire clusters were validated through discussions with fire brigade members and domain specialists to ensure alignment with real-world scenarios and operational needs. The assessment focused on their performance in terms of density-based grouping, parameter flexibility, noise handling, and computational efficiency. As depicted in Figure 2 (a) and (b), both HDBSCAN and OPTICS demonstrated strong capabilities for density-based clustering, which can be advantageous in certain applications. However, these algorithms were less suitable for this work, as the primary objective was to group fire hotspots based on spatial proximity while ensuring that single hotspots were not classified as noise, evident in areas with sparse fire detections. Furthermore, another limitation of both HDBSCAN and OPTICS was their reliance on density thresholds, requiring fine-tuning parameters such as neighborhood radius. This often resulted in single hotspots being excluded as noise, negatively impacting the visualization and usability of the data in the decision-support service.

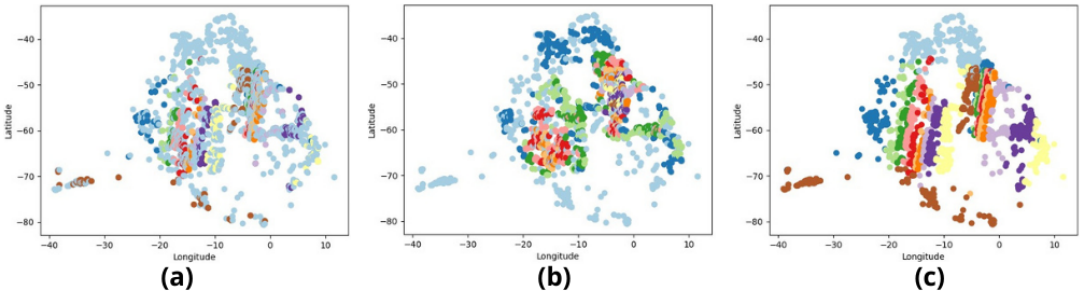

Figure 2. Clustering results of fire hotspots using three different algorithms: (a) OPTICS, (b) HDBSCAN, and (c) DBSCAN. The X-axis and Y-axis represent longitude and latitude, respectively. Each point corresponds to a fire hotspot, and the colors represent distinct clusters formed by each algorithm.

DBSCAN, on the other hand, emerged as the most suitable algorithm for this context. As illustrated in Figure 2 (c), DBSCAN effectively grouped spatially proximate hotspots while maintaining the flexibility to include individual hotspots as clusters when appropriate. Considering the generated clusters, DBSCAN was able to manage both densely packed hotspots and isolated points. This capability aligns well with the operational requirements of the decision-support service. Additionally, DBSCAN demonstrated superior efficiency in calculating distances between hotspots and their respective centroids, a critical feature for future enhancements of the service that will leverage centroid distances for advanced data analysis and visualization. In terms of computational performance, statistical analysis using a T-Student test showed no significant differences in execution times among the evaluated algorithms, with average[7] execution times ranging

[7] The clustering process was performed 10 times per algorithm.

between 4 and 5 seconds. Furthermore, the number of clusters generated by DBSCAN was more consistent with the spatial distribution of fire hotspots, ensuring meaningful aggregation of fire events, and making it the most appropriate option for the task in question.

3.5. Fire Hotspots Integration

Following the clustering process, the integration of fire hotspot data represents a crucial step toward consolidating a coherent and reliable dataset. This process combines information derived from the *FIRMS* and *BDQueimadas* databases, unifying records that originating from different satellite constellations, temporal resolutions, and processing methodologies. The integration is not merely a data-merging task but rather a methodological approach designed to improve the reliability and interpretability of fire detections in complex environmental contexts, such as the semi-arid Caatinga biome.

The rationale for integrating these two sources lies in the complementary nature of their observation strategies. The *FIRMS* platform, operated by NASA, provides near real-time detection of active fires based on data from the MODIS and VIIRS sensors, which offer high temporal frequency and rapid availability. In parallel, the *BDQueimadas* database, maintained by the Brazilian National Institute for Space Research (INPE), compiles fire reports across Brazil, generated from multiple satellite sources and consolidated by the INPE's fire monitoring program. This system provides continuous near real-time updates, generating new hotspot reports approximately every ten minutes, and serves as an authoritative reference for identifying fire hotspots officially recognized by the national monitoring agency. Together, these datasets offer a balanced combination of global coverage, temporal agility, and national validation.

Despite their shared purpose, occasional discrepancies between the two sources are expected. A single fire event may appear in one dataset but not in the other, primarily due to environmental and orbital conditions at the time of the satellite overpass. Factors such as cloud cover, smoke plumes, atmospheric humidity, and observation geometry strongly influence the thermal signals captured by satellite sensors. For instance, during a satellite pass, dense clouds or smoke layers can partially obscure the thermal signature of an active fire, resulting in a missed detection (false negative). Likewise, off-nadir viewing angles, when the sensor views the surface at an oblique trajectory, can distort the spatial footprint of the thermal pixel and reduce the effective resolution, thereby affecting the accuracy of hotspot localization. These phenomena are well documented in the remote sensing literature and represent intrinsic limitations of optical fire detection systems.

Although both *FIRMS* and *BDQueimadas* operate with high update frequencies, their independent satellite constellations and detection algorithms may still produce temporal or spatial mismatches. Even when synchronized at-ten minute interval, variations in orbital paths, revisit times, and processing criteria can lead to subtle differences in detection timing or spatial position. These divergences are not necessarily errors but reflect the distinct observational perspectives of each system, influenced by factors such as satellite altitude, sensor calibration, and atmospheric interference.

The integration of both sources mitigates these uncertainties by cross-referencing coincident detections and reconciling temporally and spatially overlapping records. The system produces a unified and high-confidence layer of fire hotspots that incorporates the strengths of each dataset. *FIRMS* contributes global near real-time agility and continuous monitoring, while *BDQueimadas* enhances the dataset with nationally validated, multi-sensor detections officially recognized by INPE. This dual-source strategy reduces the likelihood of false negatives and false positives, fills observational gaps caused by transient cloud cover, and increases the overall robustness and reliability of the decision-support system. Furthermore, integrating both sources introduces redundancy into the data acquisition process [Vieira et al. 2024]. In cases where one service experiences temporary unavailability or latency, the complementary source ensures continuous monitoring, thus increasing the overall resilience and reliability of the operational system.

Beyond enhancing data reliability, the integration fosters a deeper understanding of fire dynamics and the operational challenges of monitoring wildfires in tropical dry regions. It enables analysts and decision-makers to distinguish transient detection inconsistencies from genuine environmental variations, resulting in more accurate assessments of fire risk, intensity, and recurrence. Ultimately, this multi-source integration approach strengthens the analytical foundation of the proposed system, ensuring that subsequent visualization, notification, and predictive modules operate on a trustworthy and comprehensive representation of fire activity across both space and time.

Figure 3 illustrates the spatial integration of fire hotspot data obtained from the *FIRMS* and *BDQueimadas* databases across the state of Paraíba, covering a one-week period from October 20 to October 27, 2025. Each marker represents a fire detection recorded during this time frame: blue circles indicate hotspots detected exclusively by *BDQueimadas*, red triangles represent detections exclusive to *FIRMS*, and green crosses correspond to overlapping detections identified by both systems. The background map shows depicts the territorial boundaries of Paraíba, subdivided into its four CRBM regions.

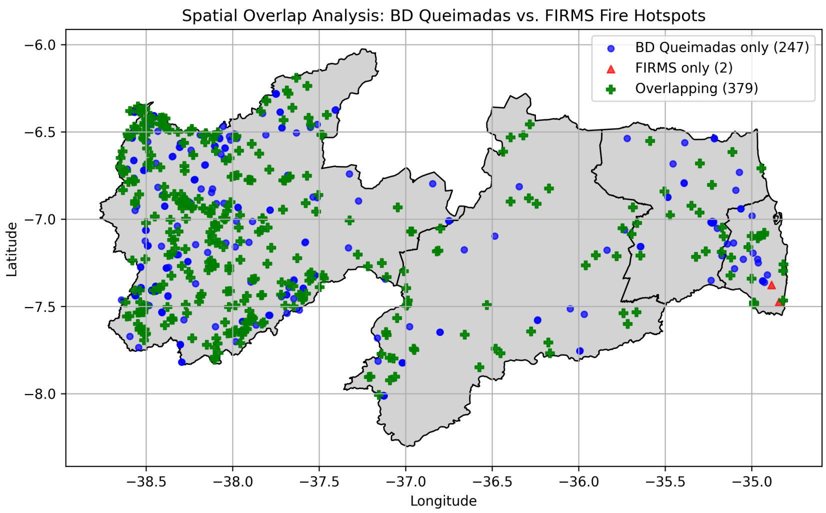

Figure 3. Geographical division of Paraíba into four CRBMs, with the *Parque Nacional da Serra do Teixeira* highlighted in red.

As shown in the Figure 3, the highest concentration of hotspots is observed in the western and central portions of the state, corresponding to the semi-arid regions of the Caatinga biome. This spatial pattern is consistent with historical records indicating a higher frequency of fire occurrences between September and January, the hottest and driest months of the year in Paraíba [Alves et al. 2021, Bello et al. 2023]. The high density of overlapping detections (in green) demonstrates strong spatial agreement between the two monitoring systems, confirming the consistency and reliability of the integrated dataset. Conversely, the presence of non-overlapping points (in blue or red) highlights natural variations resulting from orbital differences, atmospheric conditions, and distinct detection algorithms used by each satellite constellation. These divergences are systematically analyzed and reconciled during the fusion process to ensure spatial and temporal coherence.

The joint use of NASA and INPE monitoring infrastructures illustrates an effective model of inter-institutional collaboration, promoting the integration of global and national capabilities for environmental risk management. In addition to improving data reliability, the integration process demonstrates the architectural flexibility of the system to incorporate new data sources in the future. The modular design of the data ingestion and fusion components enables the seamless integration of additional fire monitoring datasets, meteorological layers, or IoT-based environmental sensors. This extensibility ensures that the platform can evolve alongside advances in satellite technology and national monitoring infrastructures, reinforcing its long-term applicability and scalability.

The integration process consolidates all detections into a unified hotspot database, which serves as the foundation for real-time visualization, analysis, and alert generation. By maintaining a single, harmonized dataset, the system enhances both the completeness and confidence of fire information used by emergency response teams. This unified view allows the Fire Department of Paraíba to operate with higher situational awareness, particularly during peak fire seasons, reducing uncertainties and supporting rapid, evidence-based decision-making. The combination of global and national monitoring sources thus reinforces the analytical robustness and operational reliability of the entire decision-support infrastructure.

4. Application and Practical Deployment

As a result of this work, a decision-support service was developed, which supports fire brigades through a mobile application and a BI interface[8]. As a first step, users should log in to the application using their credentials to enhance security and prevent unauthorized access. After logging in, the user will be able to view a map displaying all fire outbreaks that occurred within the last 48 hours (the user can configure the time period). Since this project is focused on the state of Paraíba in Brazil, where the Caatinga biome covers approximately 90% of the territory, only fire outbreaks occurring in this region will be displayed. However, this project can be extended to provide information related to other states, regions, or biomes.

As illustrated in Figure 4 (a) and (b), users can switch between different map

[8]https://fm-ifpb-datalab.web.app/map

styles, including terrain (relief), satellite, road map, and hybrid (with roads and terrain information). We used the Mapbox SDK[9] for React Native to render maps, providing a dynamic and real-time user experience. Furthermore, the mobile application displays the precise locations of all detected fire outbreaks, assisting firefighters in understanding the surrounding environment, including nearby roads, mountains, buildings, and water sources. This information can facilitate or hinder firefighting efforts. If *FIRMS* delays or fails to report a fire, the application allows users to add the fire outbreak to the map manually. At the top of the screen, a black bar displays four key climate metrics relevant to firefighters, tailored to your location: wind speed, temperature, humidity, and precipitation chances. Therefore, it is important to emphasize the significance of this mobile application in delivering valuable and real-time information to firefighters via their smartphones, even during challenging firefighting operations.

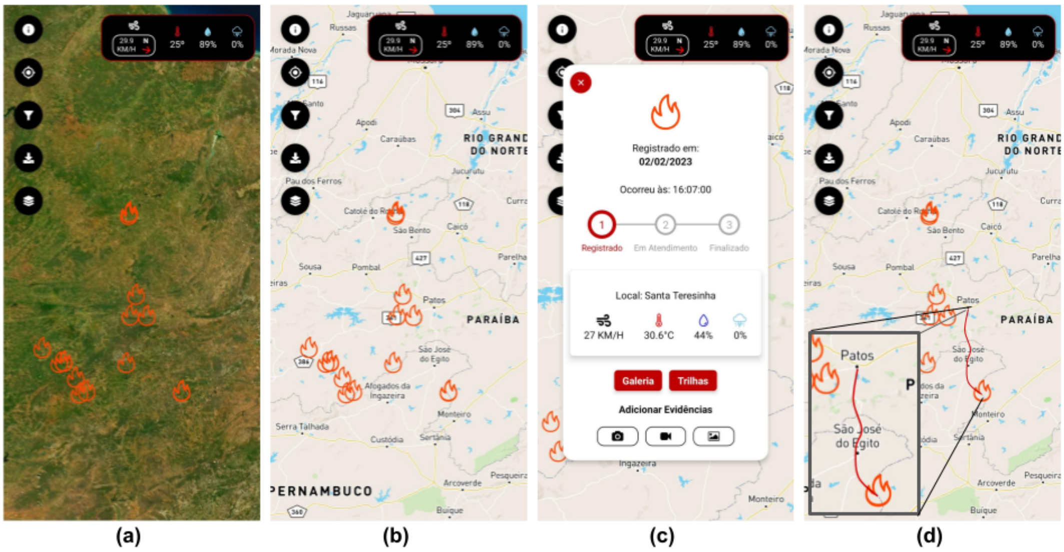

Figure 4. Screens of the proposed application: (a) fire outbreaks in satellite image view; (b) fire outbreaks in road view; (c) details of a specific fire outbreak; (d) a possible track to the fire outbreak.

By clicking on the fire outbreak icon, users can access additional information about the specific fire, including the city name, weather conditions, and timestamp of the fire registration, as shown in Figure 4 (c). When a user adds a fire outbreak, their user profile also appears as additional information. To manage the fire outbreak, firefighters can change its status to one of the following: i) registered (fire is recorded in the system); ii) in attendance (firefighters are dispatched to the scene); and iii) concluded (fire is extinguished). The fire status helps firefighter units manage their operations and provides valuable analytical data on the ratio of attended fires to all registered fires.

An essential functionality of the app is the ability for users to upload videos and photos specific to a fire outbreak, as shown in Figure 4 (c). Therefore, based on the recorded images and videos, firefighters approaching the fire can assess its size and scope

[9]https://www.mapbox.com/

in real-time. This information is useful for planning and coordinating firefighting efforts. Another piece of information that can be associated with a specific fire outbreak is possible tracks. It is important to note that firefighters often need to walk several kilometers from roads to reach the precise location of a fire. Furthermore, these journeys often involve navigating dense forests and hard-to-reach areas. To facilitate access to the fire, firefighters can record their route and share it with others, as depicted in Figure 4 (d).

An additional feature incorporated into the mobile application is the notification system based on CRBM zones (Regional Fire Commands – *Comandos Regionais de Bombeiro Militar*). The state of Paraíba is divided into four CRBMs, each responsible for supervising and coordinating firefighting and rescue operations, as well as implementing community safety initiatives within its territorial jurisdiction. These regional commands are fundamental for the operational structure of the Fire Department, acting as intermediaries between local battalions and the central command to ensure rapid coordination, resource distribution, and continuous training of firefighting units.

Figure 5 illustrates the geographical division of the state of Paraíba into CRBM regions, represented in different colors: the 1st CRBM in gray, the 2nd in blue, the 3rd in green, and the 4th in yellow. Among them, the 2nd and 3rd CRBMs encompass the extensive semi-arid territories of the Caatinga biome, where the majority of wildfire occurrences are concentrated. The map also highlights, in red, the *Parque Nacional da Serra do Teixeira* (PARNA Serra do Teixeira), a federally protected area established by Decree No. 11,552 of June 5, 2023. This national park, located within the jurisdiction of the 3rd CRBM, represents a critical ecological zone for biodiversity conservation and wildfire prevention. Although the park lies entirely within the operational territory of the 3rd CRBM, its management involves joint responsibility between the State of Paraíba and the Federal Government due to its status as a national conservation unit. The park's geographic characteristics and ecological relevance demand precise coordination between environmental authorities and the fire brigade to ensure effective monitoring and rapid response during the dry season, when wildfire risks are significantly heightened.

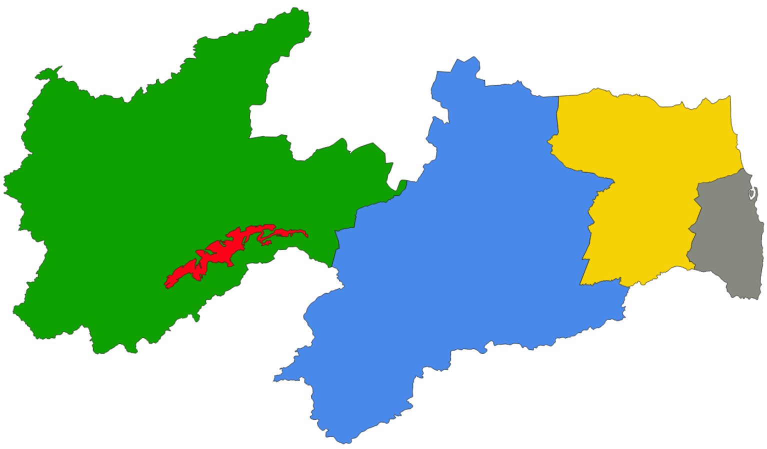

Figure 5. Geographical division of Paraíba into four CRBMs, with the *Parque Nacional da Serra do Teixeira* highlighted in red.

To address this operational need, the mobile application includes a configuration option that allows each firefighter or manager to associate their user profile with a specific CRBM. Once configured, the system automatically monitors all fire occurrences detected within the territorial boundaries of that CRBM. Whenever a new fire outbreak is registered, either through satellite data ingestion or manual reporting by users, the system performs a spatial verification to determine which CRBM zone the incident falls into. Based on this geofencing mechanism, real-time push notifications are sent directly to the mobile devices of all users affiliated with that regional command.

This functionality ensures that each CRBM receives targeted and relevant notifications, eliminating unnecessary alerts from other regions and enabling local units to respond rapidly to incidents within their jurisdiction. Furthermore, since the system is directly linked to the monitoring of the *Parque Nacional da Serra do Teixeira*, it also provides valuable support for other governmental institutions involved in environmental management and disaster response. Among these are the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), the Chico Mendes Institute for Biodiversity Conservation (ICMBio), the State Civil Defense, and the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN). The integration of this CRBM-based notification service therefore extends beyond firefighting operations, contributing to a broader ecosystem of environmental monitoring and inter-agency coordination, ultimately enhancing both responsiveness and situational awareness across the state.

Another essential component of the decision-support service is the BI interface, illustrated in Figure 6. This module plays a crucial role in transforming raw environmental and operational data into actionable insights for decision-makers. By integrating data analytics, visualization, and monitoring dashboards, the BI component provides a comprehensive view of the firefighting activities, environmental indicators, and spatial patterns of wildfire occurrences across the state.

The BI interface is designed to support managers, analysts, and policymakers in the planning and coordination of firefighting operations. It presents a set of interactive dashboards containing indicators such as the total number of detected fires, number of services performed, average response time, mean temperature and precipitation rates, as well as the number of active records in the system. These key performance indicators (KPIs) are automatically updated through the data pipeline and can be filtered by date, region, or CRBM zone, allowing users to conduct temporal and spatial analyses in real time.

The upper section of the dashboard, shown in Figure 6, summarizes high-level metrics that provide a quick overview of the current operational situation. Below, line and bar charts provide a detailed temporal analysis, including the *growth index* of fire detections, the distribution of occurrences per day, and the differentiation between day and night shifts. The *intensity* chart estimates the average brightness of fire spots, derived from satellite observations, and correlates with the energy released by the fires. This parameter is especially valuable for identifying months or weeks with higher fire severity, enabling managers to anticipate critical periods and allocate resources more efficiently,

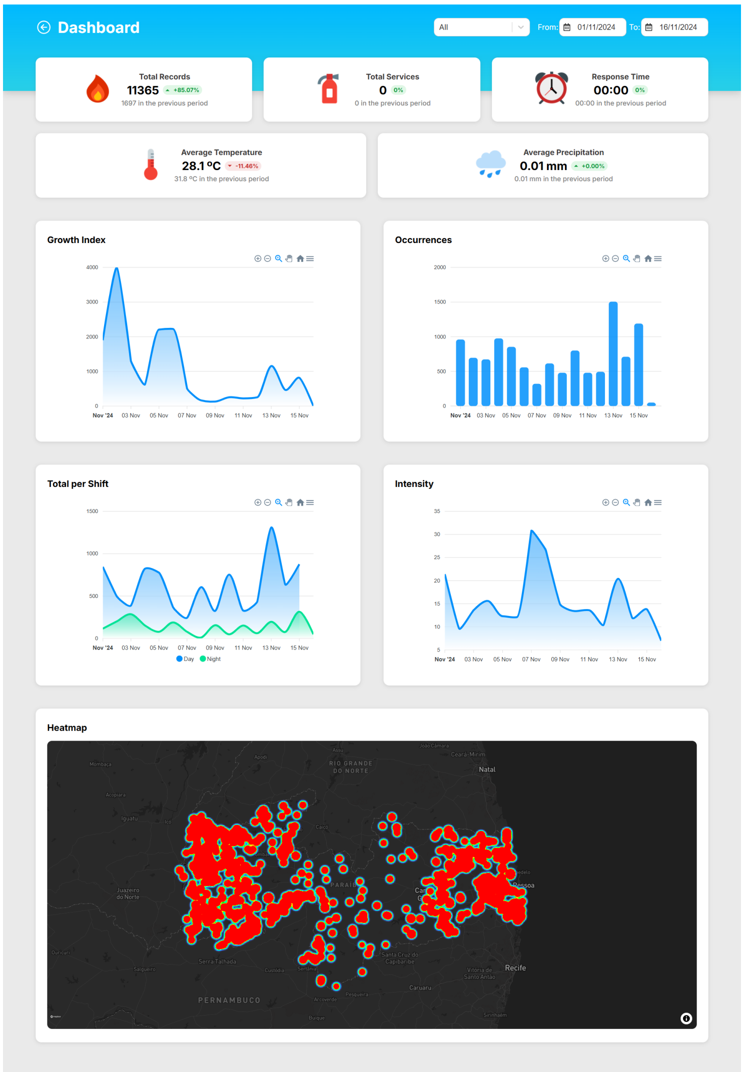

Figure 6. Example of graphs in the BI interface, which show information regarding fire spots throughout the year.

both in terms of personnel and equipment.

The BI platform also integrates meteorological indicators such as temperature and precipitation averages, which are crucial to understanding the correlation between climatic factors and fire behavior. These insights support predictive assessments that can guide proactive actions, such as preventive patrols and early deployment of firefighting teams during expected high-risk periods.

At the bottom of the dashboard, the *heat map* visualization provides a spatial representation of fire concentration across the state. In this two-dimensional layer, colors indicate the relative density of fire outbreaks, where cooler tones correspond to areas of low incidence and red zones highlight regions with intense or recurring fire activity. This information is particularly useful for identifying critical hotspots and areas that may require targeted surveillance or investigation. For instance, a persistent cluster of fire events in the same area over time may suggest recurrent anthropogenic ignition patterns, often linked to illegal land clearing or agricultural expansion.

Beyond operational monitoring, the BI interface provides valuable information for long-term strategic planning and environmental policy formulation. Government agencies and partner institutions can use these analytical dashboards to evaluate trends, allocate resources, and prioritize investments in prevention, training, and equipment. In doing so, the BI system extends the impact of the decision-support service from immediate firefighting operations to broader data-driven governance, promoting efficiency, transparency, and evidence-based decision-making.

During 2022 and 2023, we conducted software and user tests in controlled environments to evaluate the proposed tool, resulting in a significant reduction in errors when deployed in real-world contexts. Based on error reports, improvements were implemented across all interfaces of the tool. Currently, the app has been deployed at the Fire Brigade of Paraíba, supporting the firefighting in the Caatinga region. Regarding the BI module, historical data is being collected. With the use of the app by firefighters, an increasing number of data will be stored. From them, the reports have already been made available so that firefighters and managers can apply them as a decision-support tool.

5. Results and Discussions

To assess the performance, effectiveness, and usability of the proposed system, we conducted a series of tests in both controlled environments and real firefighting operations. The evaluation was divided into two main aspects: quantitative and qualitative metrics.

5.1. Quantitative Evaluation

The quantitative analysis focused on measuring the technical performance of the system across three main indicators: response time, update frequency, and data accuracy.

Response Time. The ETL process was evaluated for response time to ensure timely data processing and delivery across the system. Performance tests indicate that the ETL pipeline completes data extraction, transformation, and loading within an average of 1.34 minutes, based on data processed in 2024 and 2025. This time frame is achieved through the use of parallel data extraction and asynchronous processing, allowing the back-end to handle large data volumes efficiently. Additionally, optimized data transformations, such as data standardization and cleaning routines, are executed with minimal delays. The NoSQL database structure supports rapid data loading and retrieval, ensuring that users can access up-to-date information with minimal latency, even under high-demand conditions. Moreover, performance tests were conducted to measure how quickly the system processes and delivers information to users in real-time. The average response time ranged from 500 ms to 2 seconds, depending on the complexity of the requests (such as loading meteorological data and satellite images). This performance is considered adequate for field operations, where the need for prompt responses is critical. Latency was minimized by using asynchronous APIs and an optimized NoSQL database for fast querying.

Update Frequency. The update frequency is carefully managed to balance data freshness, operational efficiency, and cloud infrastructure costs. Currently, the system performs a full data refresh every hour, retrieving new satellite and meteorological information while maintaining synchronization between the *FIRMS* and *BDQueimadas* datasets. Since BDQueimadas updates are available every ten minutes, an adaptive temporal window is applied to align the most recent records from both sources during each hourly cycle, ensuring temporal consistency and minimizing redundant requests. This synchronization strategy guarantees that no detections are missed between update intervals while keeping cloud processing costs at a sustainable level. Each ETL (Extract, Transform, Load) cycle averages 1.34 minutes, allowing the system to efficiently update near real-time information without compromising scalability or performance. For the mobile and web applications, back-end requests occur every 30 minutes to check for new data, manually triggered updates, or region-specific notifications. This configuration provides users with timely and reliable information while optimizing cloud resource usage for continuous, cost-effective operation.

Data Accuracy. Ensuring data accuracy is critical for reliable decision-making in wildfire monitoring and response operations. The proposed service achieves this by integrating two authoritative satellite-based monitoring systems: NASA's *FIRMS* and INPE's *BDQueimadas*. *FIRMS* provides global active fire detection using data from the MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) sensors, offering spatial resolutions of 1 km and 375 m, respectively. These sensors enable near real-time identification of thermal anomalies with high confidence levels, which are essential for pinpointing active fire events.

The *BDQueimadas* system complements *FIRMS* by aggregating national fire detections from a diverse set of ten satellite platforms that operate in the mid-infrared thermal band (around 4 μm) and are directly received by INPE. Currently, the system processes data from polar-orbiting satellites: AVHRR/3 onboard NOAA-18 and NOAA-19, METOP-B and METOP-C, MODIS sensors onboard NASA's TERRA and AQUA, and VIIRS instruments onboard the NPP-Suomi and NOAA-20, along with geostationary sensors such as GOES-16 and MSG-3. These combined sources allow BDQueimadas to provide high-frequency coverage and continuous fire monitoring across Brazil.

By cross-referencing coincident detections between *FIRMS* and BDQueimadas, the system minimizes false positives and compensates for potential omissions caused by environmental factors such as cloud cover, viewing geometry, or atmospheric interference. This integrated validation process enhances both the spatial precision and temporal consistency of fire localization, with internal tests indicating an average positional accuracy above 92%, consistent with previously reported studies [Çolak and Sunar 2020]. Consequently, field teams and command units can rely on highly consistent and timely information for hotspot detection, prioritization, and strategic planning during critical fire scenarios.

5.2. Qualitative Evaluation

The qualitative evaluation was conducted based on feedback from 10 firefighters and 2 managers, representing a portion of the volunteer users who initially accessed the service as pilot users in a beta testing format. Structured interviews and questionnaires were administered to assess usability, ease of use, user satisfaction, and the utility of the decision-support service features, providing valuable insights from real firefighting operations.

Ease of Use. The interface of the decision-support service was designed to be intuitive and easy to navigate, considering the high-pressure and high-risk operational environment. Firefighters reported that the service was straightforward to use, even in challenging field conditions, and that the simplified interface allowed quick access to critical information, such as fire location and weather conditions. The integrated navigation functionality was also highlighted as a valuable tool for improving travel to fire hotspots.

User Satisfaction. Overall user feedback was positive, particularly concerning the ability of the service to provide real-time and centralized information. Firefighters noted that the availability of accurate and timely data contributed significantly to the safety and effectiveness of firefighting operations. Additionally, the media management tool for photos and videos was considered useful, allowing documentation of fire conditions and sharing of visual information with the teams.

Utility of Features. Among the most praised features, the interactive map visualization with climate and location data was highlighted as the most useful. The BI interface, which provides an analytical view of historical fire patterns and enables preventive planning, was also well-received by managers. Based on the feedback, the BI interface allows managers to identify high-risk regions and strategically plan resource allocation, which is essential for sustainable and effective operations.

5.3. Discussion and Impact

The results indicate that the proposed decision-support service effectively supports firefighting operations by integrating diverse data sources into a single access point. The combination of quantitative and qualitative metrics suggests that the service not only performs efficiently in terms of speed and accuracy but also meets the practical needs of end users. This alignment of performance with usability demonstrates the capability of the service to deliver timely and actionable information, which is crucial for field operations.

Following positive feedback from the management team, the proposed decision-support service is being implemented within the Integrated Command and Control Center (Centro Integrado de Comando e Controle - CICC). The CICC, established to enhance public safety and facilitate coordinated emergency responses, functions as a central hub for monitoring and managing public safety efforts across the state. Integrating this decision-support tool into the CICC aims to establish it as a primary resource for state-level actions in forest fire combat and fire brigade management.

This deployment enables real-time decision-making and optimized resource allocation, ensuring that firefighting operations and related public safety initiatives benefit from centralized, continuously updated information. This approach not only enhances the tactical and strategic capacities of the CICC but also aligns with its mission to improve public safety through advanced technology and data-driven insights.

5.4. Limitations

Despite the promising results and practical applicability of the proposed system, some limitations should be acknowledged. First, the accuracy and completeness of fire detection depend on satellite observations, which may be affected by environmental and orbital conditions such as cloud cover, smoke plumes, and sensor viewing geometry. These factors can occasionally delay or obscure fire detection, particularly in highly dynamic atmospheric scenarios.

Second, the system currently operates with an hourly data refresh cycle, which represents a trade-off between operational cost and data timeliness. Although this configuration ensures stable and cost-effective operation, it may introduce a short latency in the detection and visualization of newly emerged fire events compared to fully continuous real-time systems.

Finally, the evaluation of the proposed solution was conducted primarily within the Caatinga biome, whose climatic, ecological, and environmental characteristics differ from other Brazilian biomes. Therefore, while the system architecture is scalable and adaptable, additional validation is required to assess its performance and effectiveness in regions with different vegetation density, humidity patterns, and fire behavior.

6. Related Work

According to the works [da Silva et al. 2018, Caetano 2021, Reddy et al. 2019], the impacts caused by fires in forest areas cause irreparable damage not only to the environment but also to the country's economy. Therefore, with the increasing number of fires throughout Brazil, combined with the limitations of contingent and equipment in fire brigades, becomes necessary the application of approaches that assist the decision-making and action planning to combat the forest fires. Among these approaches, the application of technology (software and sensors) emerges as one of the most promising [Çolak and Sunar 2020]. Following, we present technological solutions used around the world to combat forest fires:

- FireScope[10] - A tool that supports firefighters planning during firefighting operations in real-time. The app provides detailed information about topography, vegetation, and weather conditions, allowing firefighters to receive information regarding how to fight the fire;
- Firefighter Log[11] - An application that allows firefighters to record information about the fire, including the type of fire, the dimension of damage, and the location. The app also assists in coordinating firefighting operations between different fire units;
- FireReady[12] - Platform developed by the Australian government to provide real-time fire alerts, similar to the data provided by *FIRMS*. Also, the platform provides educative information on fire risk levels and guidance on what to do in case of fire.

[10] https://firescope.caloes.ca.gov/
[11] http://www.firefighterlog.com/
[12] https://fireready.org.au/

- Wildfire[13] - Software that allows firefighters to receive real-time information regarding the location, dimension, and intensity of forest fires across the USA country, with a focus on the state of Idaho. The software aims to support the coordination of firefighting efforts, similar to *FIRMS*, but with the scope only for the USA.

Although technological tools have been applied to combat and prevent forest fires, especially through the use of satellite images [da Silva et al. 2018] or support software [Çolak and Sunar 2020, Cazzolato et al. 2017] as the tools mentioned above, there is a lack of approaches able to centralize a large number of information in portable devices such as cellphones and tablets [Komalapati et al. 2021]. Recent research on technological solutions for wildfire management has explored diverse approaches. However, while these studies demonstrate significant advances in detection, monitoring, and routing strategies, few of them provide an integrated, field-oriented environment capable of aggregating heterogeneous data sources into a unified decision-support service tailored to the operational reality of fire brigades.

The authors of [Ramadan et al. 2024] propose an AI-driven framework that combines drones and IoT sensors for early wildfire detection and prevention. Their solution emphasizes real-time data acquisition from both aerial and terrestrial sensors, supported by deep learning models to predict fire ignition and spread. Although this architecture achieves high responsiveness, it focuses primarily on the detection and early-warning stages. In contrast, the decision-support service proposed in this work prioritizes low-cost data integration, leveraging satellite imagery, meteorological APIs, and human-in-the-loop contributions to sustain real-time monitoring and operational coordination over wide and hard-to-access territories.

Complementing this perspective, the work [Boroujeni et al. 2024] presents an extensive survey on AI and Unmanned Aerial Vehicles (UAV) approaches for wildfire management, covering pre, active, and post-fire phases. Their analysis provides a comprehensive taxonomy of UAV-based data processing, edge computing, and machine learning techniques. The survey highlights a critical gap in existing systems: while most efforts concentrate on improving detection and prediction accuracy, there is a lack of attention to post-detection decision-support capabilities and integration with command centers. This limitation reinforces the contribution of our approach, which extends beyond detection to include analytical dashboards and mobile tools designed to support both tactical and strategic decision-making in firefighting operations.

A different line of research is explored by [Tholo et al. 2025], who developed a web-based Spatial Decision Support System (SDSS) to optimize routes to forest fires using spatial data and risk zones. This system effectively supports geographic reasoning and logistical planning for firefighting units. Nonetheless, its architecture is oriented toward route optimization and static data visualization, with limited support for real-time updates and multi-source data fusion. In contrast to such SDSS solutions, our work integrates similar spatial analysis principles but extends them through real-time data ingestion, asynchronous processing, and a dual-interface design, combining a mobile application for field

[13] https://www.nifc.gov

operations and BI dashboards for management-level analysis.

In summary, while previous studies have contributed valuable components to the wildfire management ecosystem, few have operationalized these technologies within a comprehensive, scalable, and user-centered decision-support service. The present work addresses this gap by integrating real-time data collection, cloud-based analytics, and intuitive visualization tools to enhance situational awareness and coordination among firefighting teams. Moreover, to the best of our knowledge, none of the fire brigades in Brazil apply software similar to the one proposed in this work. To this end, we developed this decision-support service specifically tailored to the needs of the Caatinga region and optimized for the requirements of the local firefighting teams. Thus, we include features and functionalities that address the unique demands of firefighting in this environment. Besides, this decision-support service can benefit from a continuous cycle of development and adaptive learning. This means an evolution based on feedback from firefighting teams and the specific needs of the Caatinga region over time. For this reason, [Çolak and Sunar 2020, Cazzolato et al. 2017] highlight the importance of applying complementary data to support the planning and actions related to firefighting. Thus, the development of a mobile application able to provide useful information to firefighters before, during, and after the firefighting, allows financial gains (in the sense of equipment and staff management), environmental (preservation of fauna and flora), and politics (better management and allocation of public resources).

7. Conclusion and Future Works

The tool developed in this work assumes a fundamental role in fighting forest fires in the Caatinga region. By providing important information such as the exact location of the fire, the weather conditions of the affected area, and the direction of the wind. Firefighting units can achieve effective decisions through reliable information related to the fire and protect human life and local wildlife. Moreover, the proposed tool can also support the planning and coordination of firefighting teams. For instance, determining where to position firefighting resources, including aircraft, vehicles, and fire crews, to maximize the effectiveness of firefighting efforts.

The quantitative evaluation shows an average response time under 2 minutes, approximately 92% fire location accuracy, and consistent hourly data synchronization, evidencing significant improvements in operational awareness and decision-making support. Furthermore, as stated, the app is being used by the managers and firefighters hosted in the Fire Brigade of the Paraíba, supporting the firefighting at the Caatinga region. The first feedback reported by the users is positive in the sense of supporting the planning tasks as well as the actions related to firefighting. From the feedback, the components of the tool will be reviewed and technical adjustments may be necessary.

For future work, we aim to expand the deployment of the service to other Brazilian fire brigades and potentially to other biomes with distinct environmental characteristics. In addition, we plan to incorporate predictive analytics through machine learning models capable of learning from historical fire, meteorological, and environmental data. Such models may support fire risk prediction, anomaly detection, and early warning mechanisms. By integrating artificial intelligence with real-time monitoring and multi-source data fusion, the system can evolve from a reactive monitoring platform into a proactive wildfire risk management tool.

Finally, further investigation into scalability, parameter sensitivity in clustering algorithms, and integration with additional environmental data sources will be conducted to enhance robustness and adaptability. Overall, this study demonstrates how an integrated Information Systems approach can bridge technology, organizational coordination, and environmental management to address complex societal challenges such as wildfire response in vulnerable ecosystems.

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