Real-Time Monitoring System for Forest Fire Prevention and Combat: A Case Study in the Brazilian Semi-Arid Region

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Abstract

Context: Wildfires pose significant environmental, economic, and social challenges, particularly in dry tropical forest biomes, such as Caatinga in Brazil. Traditional firefighting approaches often lack real-time data, impacting the efficiency of firefighting teams.

Problem: Current firefighting operations lack integrated technological tools that support decision-making with real-time data on fire outbreaks, weather, and regional geography. This gap in operational support can lead to delayed responses, increased resource consumption, and compromised safety.

Proposed Solution: This study presents a comprehensive decision-support service that aggregates real-time data from IoT sensors, satellite imagery, and weather APIs into an integrated system. This service equips firefighting teams with advanced tools for tracking, weather updates, fire management, and strategic planning, centralizing actionable information to enhance response capabilities.

IS Theory: The proposed system is based on General Systems Theory, which supports interconnected subsystems for data collection, analysis, and user interaction, collectively enhancing operational support and strategic planning in firefighting.

Method: A case study approach was applied, implementing the service for a regional fire brigade. Data from various sources were collected, processed, and displayed through an integrated system, including both a mobile and web application. System performance was evaluated using quantitative and qualitative metrics.

Results Summary: The decision-support service provides real-time fire monitoring and aids in efficient firefighting planning and operations. Positive feedback from users indicates improved situational awareness and resource allocation.

Contributions and Impact in IS: This tool enhances Information Systems by enabling actionable insights and real-time operations. Its scalable architecture adapts to various biomes, showcasing the value of integrated technologies in managing complex challenges and transforming traditional disaster response practices.

CCS Concepts

• **Information systems** → **Decision support systems**; • **Applied computing** → *Environmental sciences*; Surveillance mechanisms.

Keywords

Forest Fire, Mobile Application, Business Intelligence, Decision-Support Systems, Real-Time Monitoring

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 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 [23]. Firefighting in vegetation areas is complex, requiring skilled planning, coordination, large teams, and diverse resources. Specifically, fighting fires in dry forests involves challenges such as identifying the affected area, assessing nearby water sources, terrain, and roads, as well as effectively deploying staff and equipment (cars, trucks, and flame-fighting items) [8, 15].

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 [6, 8, 13]. This work proposes the development of a 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.

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

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.

The system is scientifically original by combining real-time data analysis with advanced visualization and forecasting techniques, creating a new approach to firefighting. 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 [10]. 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 [11]. 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 [4, 13]. 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 [10, 20, 24]. 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 [2]. These platforms provide real-time data (e.g., fire spread, flooding, deforested areas, and hotspots) to identify and prioritize areas for intervention. Work such [22] highlights the benefits of remote sensing platforms over different kinds of environmental anomalies. Regarding GIS applications, [18, 25] 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. These sensors provide valuable insights, which allies with remote sensing platforms and GIS can support timely decision-making and response efforts, as discussed in [9, 21]. 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 [17], the authors propose the application of techniques and tools of BI to expose the patterns of vulnerability and risk in

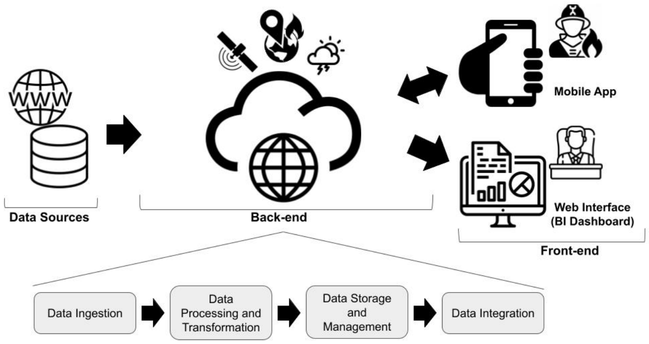

Figure 1: The project architecture of the proposed application.

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 [12], 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 [8, 23]. 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 proposes 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 geospatial data from OpenStreetMap[5]. 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 complex 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 is handled using Cloud Firestore, a NoSQL database selected for its flexibility in managing unstructured and semi-structured data. Cloud Firestore supports a dynamic schema, adapting to evolving data types such as satellite imagery, weather data, and user inputs. This database allows for efficient

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

[3]https://www.weatherapi.com/

[4]https://firms.modaps.eosdis.nasa.gov/

[5]https://www.openstreetmap.org/

storage and rapid retrieval of large volumes of real-time data. Hierarchical data structures are employed to represent different data types (e.g., fire locations, weather conditions, media files), facilitating flexible querying mechanisms and enabling rapid access to specific data subsets during critical operations.

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 (Fire Information for Resource Management System). 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 using 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. This data is vital for identifying fire hotspots, assessing their severity, and tracking their development in real-time.

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.

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 data is aggregated to create comprehensive and actionable information, which merges and correlates data from different sources. Spatial indexing is used to match weather data with specific fire locations, and time-based filtering ensures that only the most relevant and up-to-date information is incorporated. This integrated dataset drives both the mobile application and the web interface, providing users with a holistic view of the situation.

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 Cloud Firestore, 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 Cloud Firestore, a NoSQL database chosen for its flexibility and scalability. The hierarchical data storage model of Cloud Firestore 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 Cloud Firestore 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. Cloud Firestore 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 [1], HDBSCAN [16], and DBSCAN [14]. 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 2 (a) and (b), both HDBSCAN and OPTICS demonstrated strong capabilities for density-based clustering, which can be advantageous in

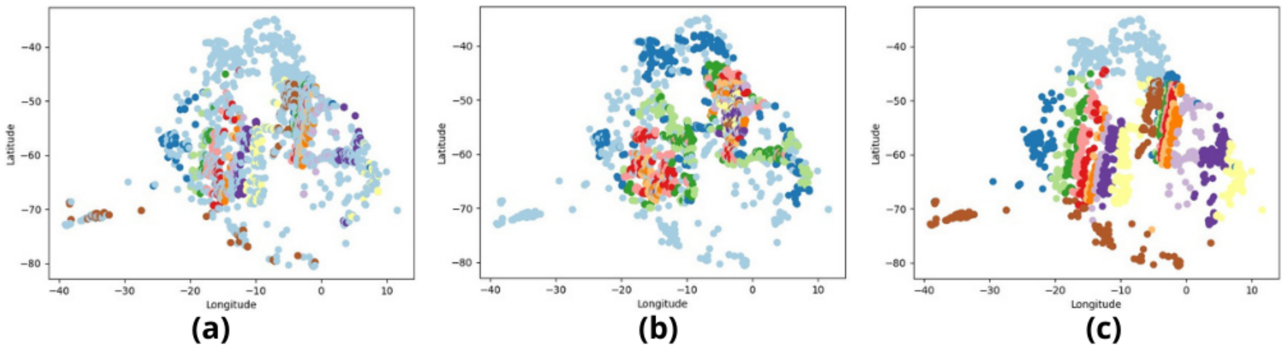

Figure 2: Clustering results of fire hotspots using three different algorithms: (a) OPTICS, (b) HDBSCAN, and (c) DBSCAN. The X-axis and Y-axis represent longitude and latitude, respectively. Each point corresponds to a fire hotspot, and the colors represent distinct clusters formed by each algorithm.

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.

DBSCAN, on the other hand, emerged as the most suitable algorithm for this context. As illustrated in 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[6] execution times ranging 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.

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[7]. 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 3 (a) and (b), users can switch between different map styles, including terrain (relief), satellite, road map, and hybrid (with roads and terrain information). We used the Mapbox SDK[8] 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.

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 3 (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 3 (c). Therefore, based on the recorded images and videos, firefighters approaching the fire can assess its size and scope in real-time. This information is useful for planning and coordinating

[6]The clustering process was performed 10 times per algorithm.
[7]https://fm-ifpb-datalab.web.app/map
[8]https://www.mapbox.com/

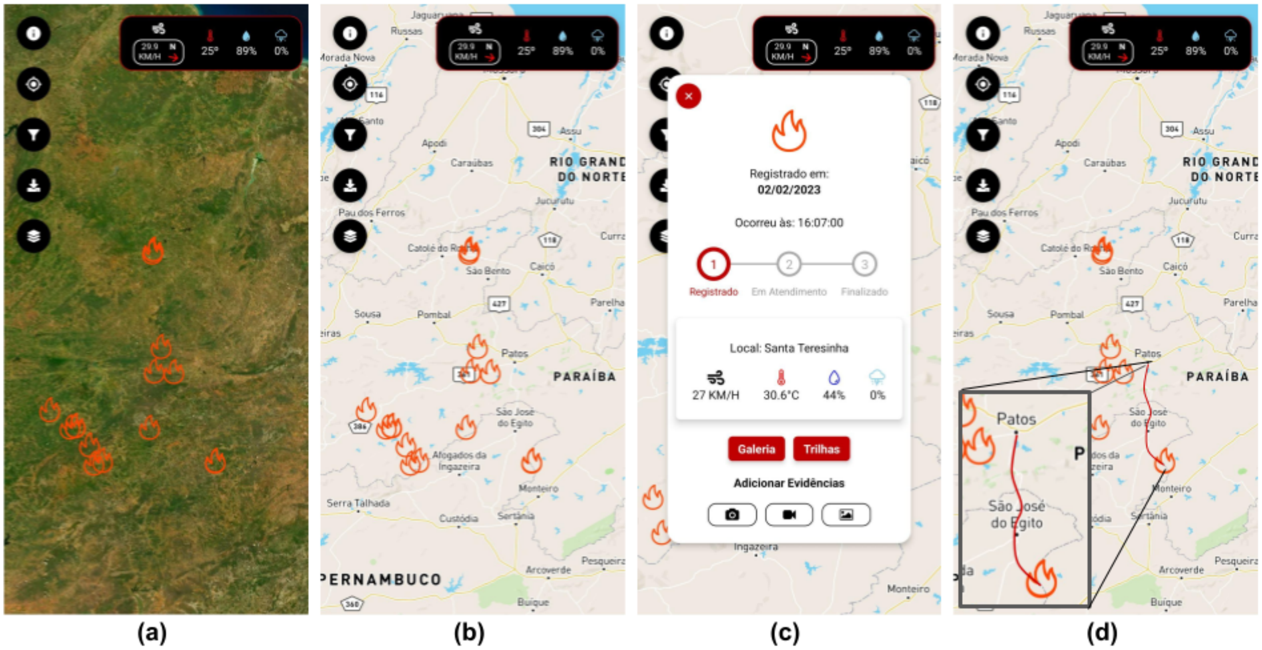

Figure 3: Screens of the proposed application: (a) fire outbreaks in satellite image view; (b) fire outbreaks in road view; (c) details of a specific fire outbreak; (d) a possible track to the fire outbreak.

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 3 (d).

Another component of the tool is the BI interface, illustrated in Figure 4. This component utilizes BI principles to generate reports (including graphs, maps, tables, and summarized data) for managers and stakeholders through web-based visualization. This interface integrates business analytics, data processing, visualization tools, and best practices to enable organizations to make informed data-driven decisions. Figure 4 illustrates line and bar graphs that display information throughout the year, such as the growth rate of forest fires, the mean fire brightness, temperature and precipitation rates, the number of manual (registered by firefighters) or automated (registered by satellites) records, and the number of fire spots requiring attendance. In practice, BI provides a comprehensive view of stored data, facilitating positive change, improving efficiency, and enabling agile adaptation to real-world changes. Figure 4 also depicts the heat map, which provides a two dimensional representation of data where values are represented by colors. In this scenario, the colors indicate the concentration of fire outbreaks in the region: green signifies a low incidence of fires, while red signifies a high incidence. This information is highly useful for analyzing regions that frequently experience forest fires, which can be due to natural conditions or criminal activity. For instance, a high concentration of fire outbreaks in the same area over a year may indicate criminal fires set to clear land for livestock farming.

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

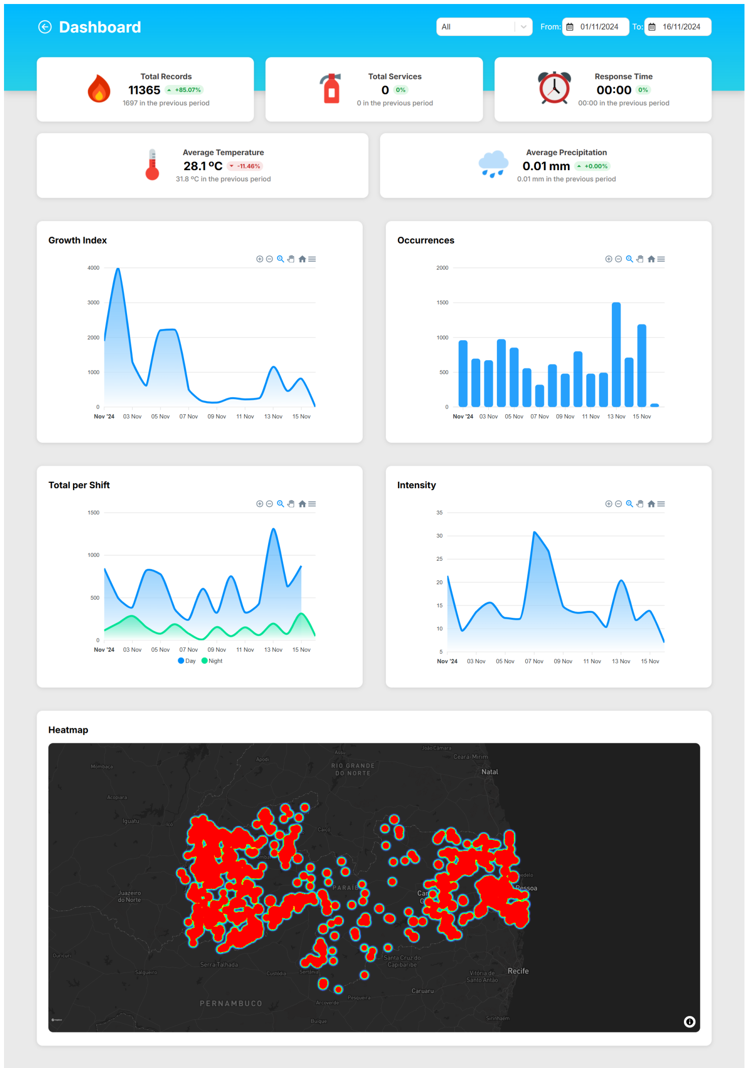

Figure 4: Example of graphs in the BI interface, which show information regarding fire spots throughout the year.

1.24 minutes, based on data processed between October and November 2024. 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 frequency of data updates is carefully managed to ensure that real-time information maintains both relevance and accuracy. Currently, the system refreshes satellite and meteorological data every 3 hours, aligning with the satellite data update cycle. This interval also helps control cloud infrastructure costs, as frequent updates significantly increase financial overhead. However, based on the service data collection and processing efficiency (with each ETL cycle averaging 1.24 minutes), updates could technically be performed within a few minutes without compromising service performance. As for the update frequency on mobile and web applications, requests to the back-end are made every 30 minutes to check for any manually triggered updates or pending notifications specific to the user. This setup ensures timely information while balancing operational efficiency and cost.

Data Accuracy. Data accuracy is essential to ensure that firefighters can make decisions based on reliable information. To achieve high accuracy in fire location data, the proposed service is anchored in FIRMS and BD Queimadas[9] sources. FIRMS provides satellite-based fire detection using data from MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) sensors. MODIS offers a spatial resolution of 1 km, while VIIRS provides a finer resolution of 375 meters, allowing the detection of thermal anomalies in near real-time and delivering high-confidence data on potential fire locations. During testing, the accuracy rate for fire location information was consistently close to 92%, which is also based on the results highlighted in [6]. As a secondary validation source, the system cross-references data with BD Queimadas, which provides historical fire records and up-to-date fire monitoring for Brazil. This multi-sources approach ensures that field teams receive precise and timely data, enabling accurate hotspot detection and strategic action planning in critical fire situations.

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.

6 Related Work

According to the works [3, 7, 19], 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 [6]. 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.
- Wildfire[13] - Software that allows firefighters to receive real-time information regarding the location, dimension, and

[9] https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/

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

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 [7] or support software [5, 6] 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 [15]. 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, [5, 6] 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

Given the challenges associated with firefighting tasks, including limited resources and equipment within fire brigades, this application paper describes the development and deployment of a service capable of collecting and integrating data from various sources. This service then provides useful information through a user-friendly interface to support fire brigades and aid in strategic planning for firefighting efforts. As stated, the service is currently in use by managers and firefighters at the Fire Brigade of Paraíba, supporting firefighting efforts in the Caatinga region.

For future work, our main goal is to expand the application of the tool to additional fire brigades throughout Brazil. Given the scalability of the proposed tool, this expansion is achievable in the near term. We plan to integrate artificial intelligence, specifically ML algorithms, to predict fire occurrences in specific regions using the data collected by our decision-support service. Also, exploring alternative clustering algorithms will be considered to evaluate potential improvements in the accuracy and efficiency of fire aggregation.

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