



Dam Monitoring Dashboard

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Computer Science and Engineering

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Dam monitoring is essential to ensure safety, support decision makers, and address water resource management issues, particularly in triggering crisis alerts. Current methods often lack real-time capabilities and rely on repetitive visualization techniques, increasing risks during emergencies. Our research addresses these challenges by developing a comprehensive dashboard that enables monitoring of critical parameters related to dam safety and performance. This innovative tool enables the exploration of dam behavior data, including water levels, temperatures, structural vibrations, and deformations. It aims to provide engineers and dam operators with actionable information on dam conditions, improving their ability to make informed decisions and effectively mitigate risks. By identifying potential risks early, the dashboard enables stakeholders to implement proactive measures, reducing the likelihood of catastrophic failures and improving overall dam safety. This work has been evaluated as a proof of concept and will evolve into a fully functional version once the integration with Laboratório Nacional de Engenharia Civil (LNEC)'s database is operational.

Keywords

Dam Monitoring; Real-time Monitoring; Dam Safety; Data Visualization; Dashboard.

Resumo

A monitorização de barragens é fundamental para garantir a segurança, apoiar o processo de tomada de decisão e otimizar a gestão dos recursos hídricos, especialmente em situações de emergência. Os métodos tradicionais, muitas vezes, apresentam limitações ao nível da monitorização em tempo real e recorrem a métodos de visualização repetitivos, o que pode comprometer a agilidade e rapidez na resposta a crises. A nossa pesquisa visa colmatar estas lacunas através do desenvolvimento de um dashboard abrangente, capaz de monitorizar diversos parâmetros críticos relacionados com a segurança e o desempenho das barragens. Esta ferramenta possibilita a análise detalhada dos dados de comportamento estrutural, incluindo níveis de água, temperaturas, vibrações estruturais e deformações. O objetivo é fornecer aos engenheiros e operadores de barragens informações precisas e atualizadas sobre as condições das estruturas, facilitando a tomada de decisões e a mitigação de riscos. Através da identificação precoce de potenciais anomalias, o sistema proporciona a implementação de medidas proativas, reduzindo a probabilidade de ocorrência de falhas graves e contribuindo para o reforço da segurança das barragens. Este trabalho foi avaliado como uma prova de conceito e evoluirá para uma versão plenamente funcional assim que a integração com a base de dados do Laboratório Nacional de Engenharia Civil (LNEC) estiver operacional.

Palavras Chave

Monitorização de Barragens; Monitorização em Tempo Real; Segurança das Barragens; Visualização de Dados; Dashboard.

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Acronyms

UI User Interface

UL University of Lisbon

IST Instituto Superior Técnico

LNEC Laboratório Nacional de Engenharia Civil

SSHM4Dams Seismic and Structural Health Monitoring for Dams

XR4Dams Extended Reality for Dam Monitoring, Simulation, and Visualization

DBB Concrete Dam Department

FFT Fast Fourier Transform

UX User Experience

1

Introduction

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Dams are increasingly important in providing essential services such as water supply, hydroelectric power, irrigation, and flood control. However, they also present significant risks to downstream communities and ecosystems if their structural integrity is compromised. Effective monitoring of dams is crucial to ensure their safety and performance under normal operating conditions and seismic actions. Traditional dam monitoring methods often lack real-time data integration and comprehensive visualization capabilities, making it difficult for engineers and operators to identify and respond to potential issues promptly.

Ensuring the safety and integrity of dams is highly important due to the catastrophic consequences of dam failures, including loss of life, property damage, and environmental disasters. Real-time monitoring and early detection of anomalies can prevent such occurrences, protect public safety, and optimize dam operational efficiency. In addition, the increasing frequency of extreme weather events due to climate change increases the need for complex and responsive dam monitoring systems, such as a dashboard.

Developing a powerful dam monitoring system to be integrated into the Extended Reality for Dam Monitoring, Simulation, and Visualization (XR4Dams) project is hard due to the complexity and variety of controlled parameters such as water levels, structural vibrations, and temperature variations. Integrating these diverse data sources in real time while ensuring reliability and accuracy is a challenging task. Moreover, offering these data in a user-friendly manner so that engineers and operators can easily interpret calls for advanced visualization techniques.

We intend to use modern technologies to create a comprehensive, easy-to-use, and real-time dashboard accessible on desktop platforms, addressing the limitations of previous works and providing a more comprehensive view of dam conditions. Our approach involves developing real-time analytical dashboards that integrate data from sensors and external sources to monitor critical aspects of dam safety, integrity, and performance. The dashboard will feature intuitive data visualizations and analysis, enabling proactive management and response to potential problems, assuring dam safety under controlled conditions. This project will build on an existing website developed by Laboratório Nacional de Engenharia Civil (LNEC) ¹, improving its capabilities with real-time data integration, advanced analytics, and improved user interfaces on a single-page dashboard.

1.1 Motivation

This work is expected to improve dam monitoring and safety. Previous dam monitoring solutions have often been limited by a lack of real-time capabilities, poor integration of diverse data types, and repetitive data visualization techniques, typically relying on line charts that are insufficient for detecting and identifying multiple step changes. Moreover, these systems have struggled to provide intuitive and accessible insights, instead presenting raw data that required expert interpretation.

The dashboard's comprehensive view of dam conditions will enable proactive management and enhance the operational efficiency of dams. In addition, by incorporating real-time and historical data analysis, the system will improve the early detection of anomalies, preventing failures and safeguarding downstream communities and ecosystems. Our case study will use data from the Cahora-Bassa Dam to offer the LNEC more straightforward visualizations of several critical parameters related to dam safety and performance.

1.2 Objectives and Deliverables

The main objective of this work is to conceptualize and develop a real-time monitoring dashboard for dam safety and performance. This dashboard aims to integrate real-time data from various sensors and

¹<https://sshm4damswebapp.vercel.app/>

external sources, such as water levels, structural vibrations, and temperature variations, into a single, user-friendly platform. The objective is to deliver actionable insights to engineers and dam operators through intuitive data visualizations and alerts, aiding in the early detection and response to potential issues. The dashboard will be available on desktop devices, enhancing decision-making processes.

This project aligns with several of the United Nations' Sustainable Development Goals (SDGs). The first is Goal 6: Clean Water and Sanitation, as structural systems such as dams play a critical role in managing water resources and generating sustainable energy. These infrastructures are essential for both communities and ecosystems. Ensuring their integrity and preventing potential disasters directly supports SDG 6 by maintaining a reliable and sustainable supply of clean water. Another important goal addressed is Goal 9: Industry, Innovation, and Infrastructure. By promoting the development and monitoring of resilient infrastructure systems through innovative technologies and sustainable practices, this project contributes to the construction of more robust industrial capabilities.

The project was executed in four phases:

- **Related Work Analysis:** This phase involved studying previous work to identify best practices, technological gaps, and potential improvements. The insights gained serve as the design and development foundations of our monitoring dashboard.
- **Requirement Gathering:** Identifying and documenting the requirements for the dam monitoring system through consultations with engineers and dam operators. This phase involves understanding the specific needs and challenges of dam monitoring to ensure that the proposed solution is tailored to address them effectively.
- **Development of Prototype:** Building a prototype of the real-time monitoring dashboard based on the identified requirements. This will include integrating sensor data, developing data visualization tools, and ensuring the system's accessibility on desktop platforms.
- **Prototype Evaluation:** Testing and evaluating the prototype to ensure its functionality, intuitiveness, and user-friendliness. Feedback from users will be collected and used to refine the system.

1.3 Thesis Outline

In addition to this introduction, the document presents, in Chapter 2, a theoretical background on data visualizations, dashboards, and dam monitoring and safety control. Chapter 3 describes related work related to different types of monitoring dashboards, but more specifically, the use of this type of technology in the dam area. The feedback from LNEC across various stages of prototype development is addressed in Chapter 4. In Chapter 5 of the document, the approach to the development of the prototype is described. The evaluation of the prototype is shown in Chapter 6, which includes user evaluation and

feedback. In Chapter 7, the conclusions concerning this work are presented, including achievements and future work.

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Background

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This background section outlines the key concepts necessary to understand the context of this project.

2.1 Data Visualizations

When implementing visualizations, it is important to consider some key factors. First, it is crucial to identify the target audience. Data visualizations are powerful tools for conveying information while also meeting the audience's expectations and needs. Another critical consideration is understanding the available tools, including knowledge of the existing options and the differences between them.

Data visualization [1] has played a crucial role in various fields for centuries. One remarkable discovery example from early history is a diagram that employs a grid system to represent the positions and movements of planetary bodies. In 1644, the astronomer Michael Florent Van Langren created a one-dimensional line graph to demonstrate the wide variations in estimates, despite the potential suitability of a tabular format for presenting such data [1]. During the late 1700s, William Playfair, often remembered as the "father" of data visualization [10], created several diagrams still used today, such as bar charts, line charts, and pie charts. One century later, in 1854, John Snow used visual representations to understand complex data. His most famous example is the map [11] he created to identify the sources of cholera, which significantly contributed to improving public health practices. In a related effort, Florence Nightingale [12] became well-known for her use of pie charts to illustrate that unsanitary conditions in hospitals were the leading cause of death among British soldiers during the Crimean War. Seven years later, in 1861, Charles Joseph Minard [1] created an important map depicting Napoleon's march, which illustrated the massive losses his army suffered during the advance to Moscow.

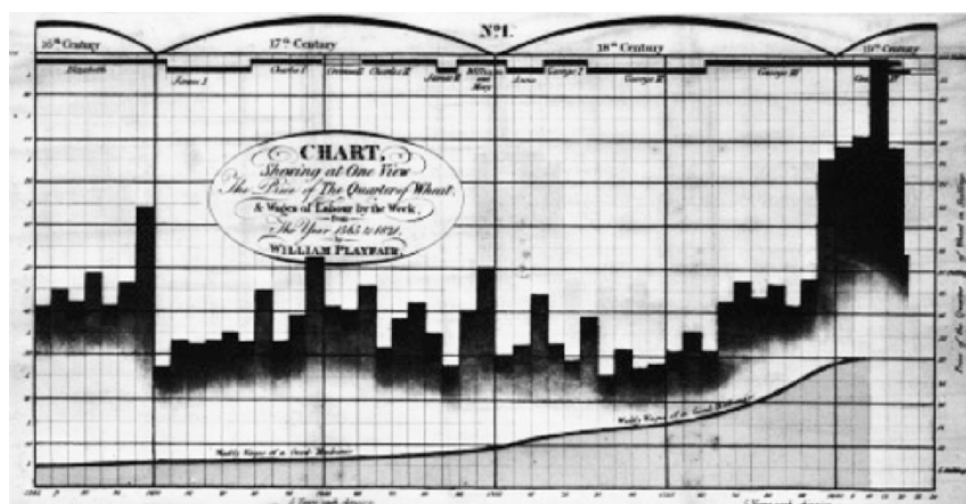


Figure 2.1: William Playfair groundbreaking work [1]

Most recently, tools [1] like Power BI and Tableau have simplified the creation of interactive, responsive, and dynamic visualizations. These tools have expanded the application of data visualization in diverse fields, including business, healthcare, and scientific research.

Computer-based visualization [13] is defined as a visual representation of datasets designed to help people carry out tasks more effectively. It is suitable when there is a need to augment human capabilities rather than replace people with computational decision-making methods. The design space of possible visualization idioms [13] is huge and full of trade-offs, and most possibilities in the design space are ineffective for a particular task, so validating the effectiveness of a design is both necessary and difficult. Visualization designers must take into account three very different kinds of resource limitations: those

of computers, humans, and displays. Visualization usage can be analyzed in terms of why the user needs it, what data is shown, and how the idiom is designed. When creating a data visualization, it is important to consider the problem domain, the data abstraction, and the tasks we want the audience to understand. Then, we must meet as refereed before the audience's expectations and needs.

Munzner [13] identified key points that all data visualization tasks should take into account. These points are categorized under Analyze, Produce, Search, and Query. In the Analyze category, the key points include discovering new knowledge that was not previously known, presenting information succinctly to tell a story or guide the audience through cognitive operations, and enjoying the visualization out of curiosity rather than a pressing need to verify or generate a hypothesis. In the Produce category, the tasks involve annotating visualizations with graphical or textual elements, recording visualization elements as persistent artifacts, and deriving or transforming new data elements from existing ones. For the Search category, the tasks include looking up information when users know both what they're looking for and where it is, locating a known target at an unknown location, browsing when the exact identity of a search target might not be known in advance, and exploring to search for information whose location is unknown. In the Query category, the tasks are identifying single target characteristics without prior knowledge, comparing similar entities of multiple targets, and summarizing to provide a comprehensive view of all the information.

2.2 Dashboards

A dashboard is defined by Stephen Few [14] as a visual display of the most important information needed to achieve one or more objectives, consolidated and arranged on a single screen so the information can be monitored at a glance. It was also defined as a visual display of data used to monitor conditions and/or facilitate understanding [2].

Dashboards play different roles [14] in business performance analysis. They are used for measuring, which involves defining and tracking key performance indicators specific to a business domain. They also serve a monitoring function by offering real-time data visualization, enabling the identification of trends and potential issues. In managing, dashboards help track progress toward goals by visualizing resource utilization and informing decision-makers about resource allocation to improve efficiency. As a communication tool, dashboards transform data into compelling narratives, highlighting successes and areas for improvement. Finally, in analyzing, dashboards encourage exploration to uncover patterns and relationships. Perhaps, one popular way to categorize a dashboard focuses attention on the type of business activity it supports. As Stephen Few said this categorization is certainly not the only way to express the types of business activities a dashboard can support. However, this is the only classification that significantly relates to differences in visual design [14]. Then, the three categories that dashboards

can be inserted into are Strategic, which provides a high-level overview of key metrics that decision-makers need to monitor the health and opportunities of the business, Analytical where the discovery of details, relationships, and patterns of data is obtained through interactivity and Operational that offers detailed insights necessary for tactical/daily operations.

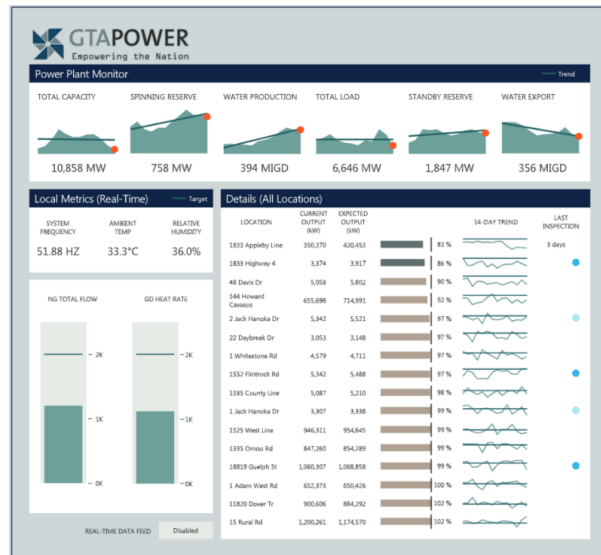


Figure 2.2: Operations monitoring dashboard [2]

Every dashboard incorporates a range of operations that enhance its functionality and usability. These operations empower users to interact with data in meaningful ways, uncover insights, and drive strategic actions. Stephen Few and Cole Nussbaumer Knaflic provide explanations of these operations through various examples of real dashboard scenarios [15].

Another common challenge is dashboard design [15]. Every detail of dashboards, from cognitive load to interactivity, responsiveness, and chart placement are crucial points in achieving a perfect dashboard. Keeping it minimal by using clear labels, intuitive navigation, and avoiding clutter can significantly enhance usability and promote a better user experience. However, there is no such thing as a perfect dashboard, which means we will never find one perfect collection of charts that ideally suits every person who may encounter it [2]. Our objective when creating a dashboard is to ensure that every main question is answered, tailored to the target audience and the dashboard's goals.

To further enhance dashboard design, here are five tips from the blog *5 Tips for Mobile-First Dashboard Design in Tableau* [16]: determine if you should optimize the dashboard for mobile by assessing the necessity of a mobile-first design. This can be done by evaluating your audience's device usage with various available tools like *Google Analytics*. Beware that not all web-safe fonts are created equal, so ensure consistent font rendering across devices, as some fonts may not display correctly on mobile. Turn off the automated phone layout and customize it manually to meet design requirements and pro-

vide the best user experience. Use tooltips to save mobile space by providing additional information without cluttering the screen and guiding users to click on elements for more details. Create a seamless scrolling experience by synchronizing multiple sheets with parameter control, eliminating individual scroll bars, and enhancing user experience.

2.3 Real-time Monitoring

To explain what real-time monitoring is, we could start by referring to the definition of monitoring provided by Slawek Ligus [17], which states that monitoring is the process of maintaining surveillance over the existence and magnitude of state change and data flow in a system. Monitoring aims to identify faults and assist in their subsequent elimination. The techniques used in monitoring information systems intersect the fields of real-time processing, statistics, and data analysis. A set of software components used for data collection, processing, and presentation is called a monitoring system.

Then, real-time monitoring involves continuously collecting and analyzing data from various system components to ensure that everything operates within defined parameters and established conditions. It enables rapid detection of anomalies, facilitating immediate corrective actions to prevent potential system failures. The systematic management and control of these processes are guided by two key elements mentioned in both [17] and [18]: metrics and logs. Metrics are collections of numeric data inputs gathered at regular intervals to track the performance and state of various system components. Logs are information recorded for diagnostic or forensic purposes, typically reviewed only when prompted by another event or issue.

To create effective real-time monitoring strategies, several practices should be adopted. We should start by defining clear key performance indicators, as referred by Slawek Ligus, that identify the most critical metrics reflecting the health and performance of a system [17]. In addition to this, it is important to make a transition to automated alerts, configuring them for anomalies or threshold breaches to ensure instantaneous responses. Using dashboards for real-time visualization of metrics and logs provides a comprehensive view of the system status. Additionally, ensure that our monitoring infrastructure is scalable to handle increased data volume as the system grows.

So, real-time monitoring is essential for maintaining the health and performance of information technology systems. By leveraging metrics, logs, and sophisticated monitoring tools, organizations can detect and address issues promptly, ensuring system reliability and performance.

2.4 Dams Monitoring and Safety

Dam monitoring is critical for ensuring the structural integrity and operational efficiency of dams, which play a vital role in providing essential services such as water supply, hydroelectric power, irrigation, and flood control. Modern dam monitoring systems use an array of sensors and data visualization tools to provide comprehensive insights into dam conditions. These systems also analyze data to predict aging and overflow risks, offering early warnings about potential issues [19].

They monitor critical parameters [20] such as average daily inflow and outflow rates, along with their monthly averages, to understand the water balance and flow dynamics of the dam. Tracking the average daily pumped and discharged flow rates ensures efficient water management. Measuring the average daily effluent flow rate and the maximum annual instantaneous flow rate aids in assessing the discharge capacity and identifying peak flow events. Hourly transferred flow rates and average daily turbinated flow rates are essential for energy production and operational planning.

Monitoring the reservoir water level and its variations over time is critical for maintaining optimal storage and ensuring safety. Daily and monthly bottom and surface discharge rates help understand sediment transport and water quality. Monthly runoff and instantaneous hydrometric levels are vital for flood management and ecological balance. Tracking the stored volume, both conventional and at the end of the month, and in the last hour, is crucial for resource management.

The data collected from these parameters is processed and visualized in an intuitive, easy-to-use dashboard interface. When certain conditions are compromised, alerting mechanisms are activated. As defined by Ligus [17], Alerting is the capability of a monitoring system to detect and notify the operators about important events that denote a grave change of state. Notifications, referred to as alerts, can take multiple forms: email, instant message, or phone call. The alert is passed on to the appropriate recipient, that is, a party responsible for dealing with the event. The alert is often logged in the form of a ticket in an Issue Tracking System, also known as a ticketing system.

Effective dam monitoring and safety practices are essential for maintaining the structural integrity and operational efficiency of dams. By leveraging modern technologies and real-time data integration, advanced monitoring systems provide critical insights into dam conditions, enabling proactive management and enhancing overall safety.

The Cabril Dam exemplifies one good scenario to implement an advanced dam monitoring system. As one of the largest dams in Portugal, it is crucial to monitor its structural integrity and operational efficiency. The existing real-time monitoring system, along with the system we create, integrates data from various sensors to ensure the safety and performance of the dam, protecting downstream communities and ecosystems from potential risks.

2.5 Context

Understanding geographic, structural, and environmental factors is essential for monitoring seismic activity and ensuring the safety of dams. This project is framed within earthquake-prone regions, where the integrity of dam infrastructure is critical to preventing catastrophic failures.

In other parts of the world, such as Japan, advanced methods have been implemented to mitigate the risks associated with earthquakes. As explained in [21], Japan's early warning system leverages the study of primary (P) and secondary (S) waves to provide alerts before significant shaking occurs. These early warnings are used to initiate automated safety measures, such as shutting down critical infrastructure and controlling dam spillways, while also informing decision-makers.

For the case study in this project, the data collection frequency can vary depending on the specific needs and constraints of the system. While real-time capabilities are not fully necessary, the application maintains a dynamic nature by collecting data at intervals that may range from days to weeks.

This dynamic nature of the web app ensures that even though it is not fully real-time, it remains responsive to changing conditions. Users can visualize historical trends, analyze seismic data, and simulate different scenarios through an intuitive interface.

3

Related Work

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The ever-growing importance of dam safety necessitates a deep dive into the latest advancements in real-time monitoring and its visualization through dam monitoring dashboards. This critical review delves into various sub-sections within this field, aiming to illuminate the relationship between real-time data acquisition, its management, and its presentation on dashboards. By exploring these interconnected areas, we aim to establish a robust foundation for the development of a dam monitoring dashboard. This framework integrates real-time monitoring data, culminating in a comprehensive real-world application designed to minimize the impact of dam failures and disasters.

3.1 Related Projects

Our dam monitoring dashboard development is a component of the XR4Dams ¹ project, which focuses on utilizing advanced technologies for dam monitoring and safety. We can benefit from leveraging previous research in various fields of monitoring dashboards.

3.1.1 Energy Dashboard by Laura Sheedy

The Energy Dashboard [3] designed by Laura Sheedy is a useful tool for monitoring and managing energy consumption across multiple facilities. This dashboard integrates various data points to provide real-time insights into energy savings, peak loads, and consumption patterns. It allows users to track energy usage over time and identify opportunities for energy savings through occupancy savings and daylight harvesting savings. The intuitive design features easy-to-understand visualizations like line graphs and area charts, making it accessible for users to grasp critical information and make informed decisions quickly.

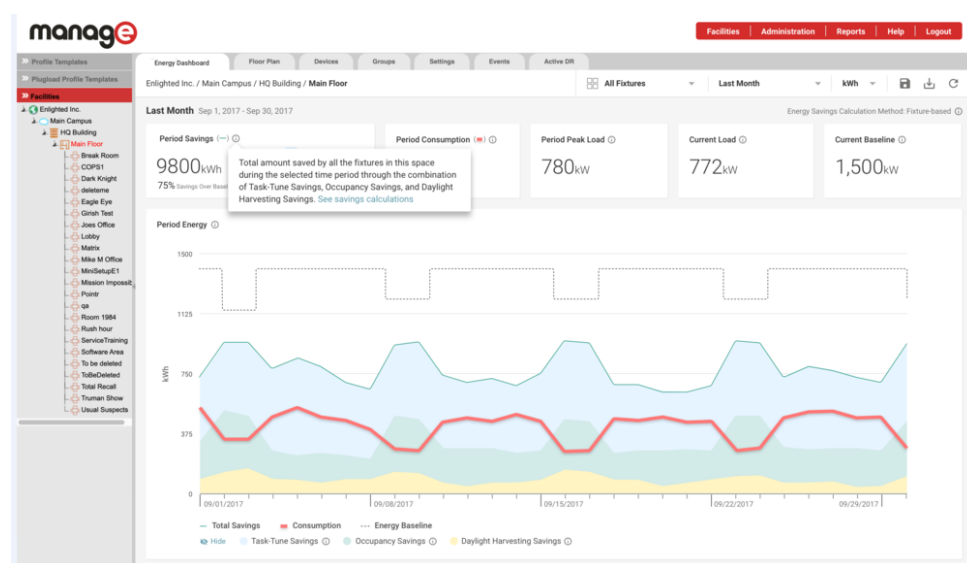


Figure 3.1: Energy dashboard by Laura Sheedy [3]

3.1.2 AVEVA System Monitor

AVEVA System Monitor [22] is a software solution designed to maintain the health and performance of AVEVA applications and their underlying hardware. It provides continuous monitoring, ensuring that critical performance indicators are tracked effectively. This system allows for proactive maintenance and reliability, ensuring system stability and integrity. This framework has several key features, ranging from

¹<https://xr4dams.tecnico.ulisboa.pt/index.html>

alerts and notifications to performance tracking. Users can receive alerts about upset conditions, which allows for timely intervention and resolution of issues. The intuitive system tracks key performance indicators, providing insights into the health and efficiency of the software and hardware in an easily navigable manner.

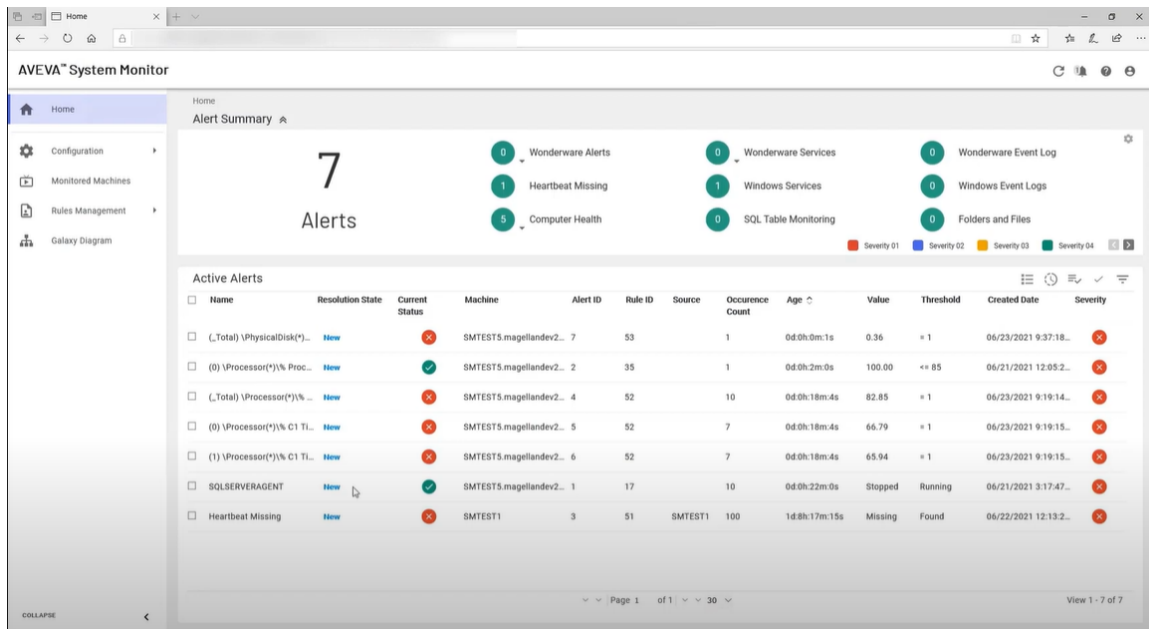


Figure 3.2: AVEVA monitoring dashboard [4]

3.2 Current Dam Monitoring Tools

Currently, several applications monitor the conditions of the dams. However, each lacks certain characteristics essential to promote dam safety and integrity. Therefore, we analyze these applications individually and then discuss their pros and cons.

3.2.1 Dam360

ADASA Systems developed a technology named *Dam360* [23] to help dam managers maintain constant vigilance on these critical structures. *Dam360* is a cloud web-based dam safety management solution. The process starts by equipping dams with various sensors, which *Dam360* can connect to and collect data from. In addition, field officers can input qualitative and quantitative dam surveillance observations, based on pre-configured route inspections, including online and offline modes of operation. Tolerance limits are applied to the data collection to minimize input errors.

All collected data synchronizes in real-time with centralized and secure cloud-based storage, making it available for analysis via configurable dashboards seconds after being collected in the field. The

Dam360 application reduces data input and transcription errors and lowers the costs of field surveillance and paper surveillance sheets. It also saves time on data collection and increases the quality and reliability of dam safety data by applying automatic quality assurance, quality control, and validation processes on incoming data.

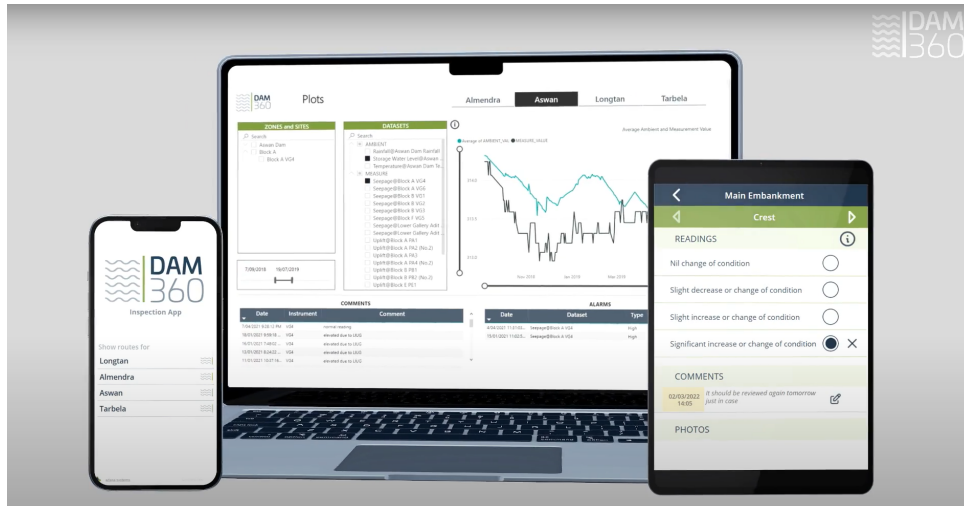


Figure 3.3: Dam360 monitoring dashboard [5]

Dam360's monitoring dashboard organizes data effectively, displaying real-time sensor readings in easy-to-understand charts, graphs, and color-coded maps, highlighting areas where sensor readings seem unusual, such as a red zone on a map indicating high pressure within the dam. The dashboard can compare current readings with historical data to identify any worrying trends. *Dam360* can be set up to trigger alerts and alarms if sensor readings exceed safe limits, allowing dam managers to be instantly notified of potential issues and take action to prevent major problems. The dashboard can be customized to prioritize the most important information for a specific dam, ensuring dam managers see this information first.

This analytical workbench allows approved users and administrators full control over the system, including input validation limits, route inspections, and scheduling. There are multiple user roles within the system, each with distinct permissions. These roles ensure that users have access to the features and data appropriate to their responsibilities.

Concluding, this multi-platform application facilitates quicker and more effective remedial actions. Dam safety engineers have real-time access to both manually collected and telemetered surveillance data. The automatic triggering of alarms and notifications in case of abnormal observations reduces the risks of potential adverse events. All dam surveillance information is readily accessible from a single system, through both static and dynamic dashboards and reports, saving time and effort in analysis and reporting and enabling more effective dam safety operations.

3.2.2 Vista Data Vision

Another sophisticated data management software designed for the advanced processing, analysis, and visualization of geotechnical and environmental data is *Vista Data Vision* [24]. Developed by Bentley, *Vista Data Vision* meets the diverse needs of dam monitoring and safety management.

Vista Data Vision stores data from various data sources in a secure, centralized MySQL database, ensuring data management and accessibility. The software facilitates comprehensive data integration. It provides powerful visualization tools, including real-time displays, personalized dashboards, and detailed graphs, allowing users to generate histograms, x-y graphs, and trend lines for effective data interpretation. These dashboards display real-time sensor readings in user-friendly formats such as color-coded maps and charts, highlighting anomalies like high-pressure zones in dams.

Vista Data Vision's alarm system triggers alerts via on-screen notifications, email, or SMS when sensor readings exceed specific thresholds, ensuring immediate response to potential issues. The software manages incoming data and sends alerts if sensor values cross alarm limits, enhancing proactive management. Users can set delays for alarms, notifying them only if the value remains in the risk range for a specified period. Additionally, the alarm messages can be customized to send different notifications based on value trends.

Another key feature is the data update limit parameter, which defines the maximum time allowed for data updates. If the data is not updated within this limit, the software notifies contact groups. This powerful tool also allows the creation of calculated variables that are mathematical functions of one or more sensor readings.

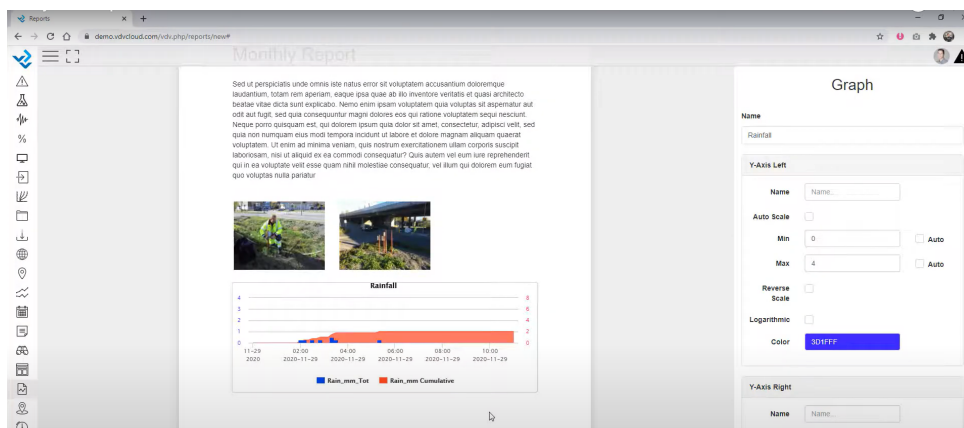


Figure 3.4: *Vista Data Vision* customizable reports [6]

Vista Data Vision includes an advanced analytics framework for complex data modeling, threshold definitions, and real-time failure mode calculations. It supports automatic report generation, facilitating efficient and comprehensive data analysis. The software offers a web service with configurable security access levels, enabling secure, password-protected access to data from any location. Multiple user

profiles can be created with customizable access rights, ensuring appropriate data access control.

This software supports automatic integration of real-time data from multiple networks, providing a holistic view of dam conditions. The intuitive graphical interface and ease of configuration make this tool accessible to users without extensive technical expertise.

Real-time data visualization and processing ensure timely responses to changes in dam conditions. Automation of data collection, validation, and reporting processes reduces manual efforts, lowers costs, and improves data accuracy. Vista Data Vision is ideal for providing critical insights into the stability and integrity of dam structures.

3.2.3 ARMS4Dams

The *Automated Real-time Monitoring System for Dams and Reservoirs* [7] is a software created by the Philippine Council for Industry, Energy and Emerging Technology Research and Development and the National Water Resources Board. This system provides real-time data on various hydrological parameters such as water levels, rainfall, humidity, temperature, atmospheric pressure, soil moisture, and wind speed.

ARMS employs wireless sensors to deliver real-time data. It monitors essential parameters for water availability and reservoir management, which are crucial for effective dam operations. The collected data supports informed decision-making regarding dam operations, especially in water utilization and flood risk management.

A significant feature of the *Automated Real-Time Monitoring System* is its web portal, *Arms4Dams*, which provides data storage and archiving. This portal allows access to information at different levels for the public, government agencies, and other stakeholders. Additionally, the system can perform hydrologic and hydraulic simulations to predict water availability and simulate potential dam overflow scenarios. These simulations help operators prepare for various climatic conditions and manage water discharge and evacuation processes effectively.

As shown in the third figure, the dashboard displays various key attributes that are being monitored. It presents data for the Binga Dam, showcasing critical hydrological parameters over the last ten days. Temperature, humidity, pressure, wind speed, soil moisture, and rainfall readings show their fluctuations and current values. These parameters are crucial for understanding the environmental conditions affecting the dam and surrounding areas. The dashboard also includes a graph depicting trends over the past ten days for all the parameters above. This visual representation helps analyze patterns and potential anomalies. Water level is shown as a percentage of total capacity, with the current level marked at 571.68 meters above sea level. This visualization explains how full the reservoir is relative to its maximum capacity. Overall, the dashboard provides a comprehensive overview of the dam's status, facilitating informed decision-making for effective water resource management and dam safety.

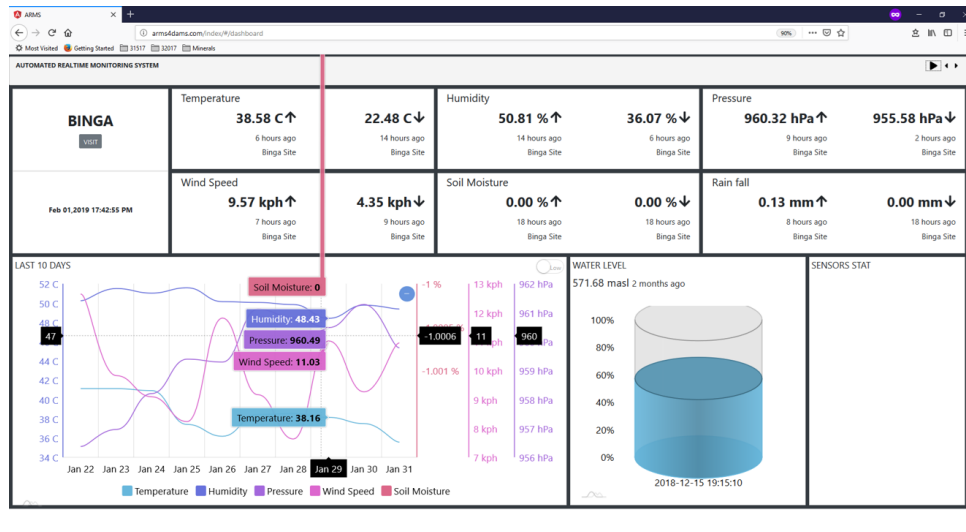


Figure 3.5: ARMS4Dams dashboard [7]

ARMS is noted for being an important solution to the needs of local water management entities. The system has been deployed in several dams along the Agno River.

3.2.4 Remote Dam Monitoring

Remote Dam Monitoring from TELNET Space [25] is a comprehensive solution designed to enhance the safety and efficiency of dam management. This software provides real-time monitoring of dams and reservoirs through continuous data collection on key parameters such as water levels, flow rates, weather conditions, and structural integrity. The system uses wireless sensors to gather this data, which is then transmitted via satellite to a central database.

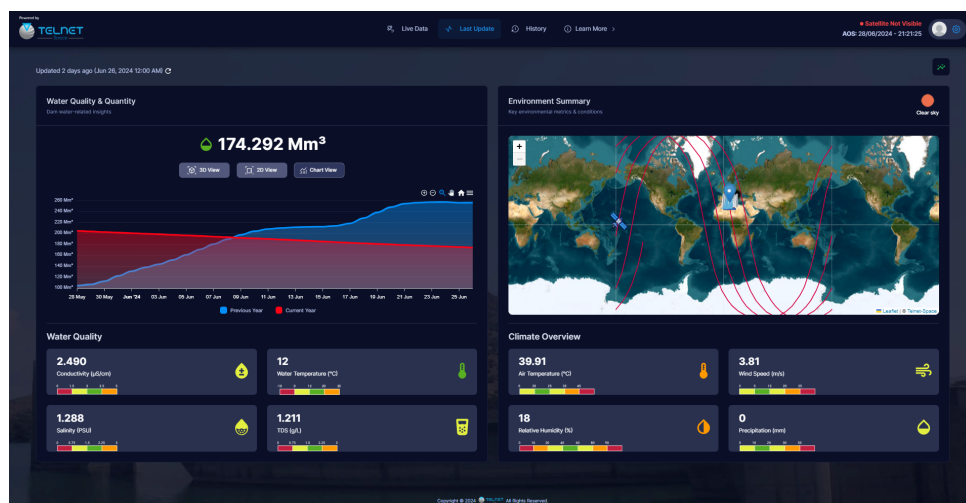


Figure 3.6: TELNET Space dam monitoring dashboard [8]

The *Remote Dam Monitoring* system excels in real-time alerts and notifications about potential issues such as rising water levels or structural weaknesses. This proactive alerting helps prevent dam failures and mitigate risks associated with flooding. The system also supports detailed data analysis and reporting, enabling predictive maintenance and informed decision-making in dam operations.

The user interface of the software offers a dashboard that displays critical parameters and trends over time, helping operators quickly assess the status of their infrastructure. This dashboard also includes graphical representations of water levels, pressure, air temperature, wind speed, precipitation, humidity, and other relevant metrics, using color scales to make it easier to identify patterns and anomalies. Additionally, tooltips in the summary section allow users to see detailed information about each dam, including its name, launch year, total capacity, and operational status.

Another important section of this software is the historical data analysis feature. This feature allows users to view trends and values of different parameters over specific time ranges, helping to identify long-term patterns and potential issues. The historical information can be displayed as an area or line chart, depending on user preference. Each chart, when moused over, displays the value at that specific time for the attribute being studied.

Overall, Telnet Space's dam monitoring solution is designed to provide a robust, reliable, and cost-effective means of ensuring dam safety and optimizing water resource management. The system's real-time monitoring capabilities and comprehensive data analysis tools make it a valuable asset for effective dam operations and risk mitigation.

3.2.5 AEM Dam Safety

The *AEM Dam Safety* software [9] is a solution designed to ensure the safety and operational efficiency of dams. The software continuously collects data from various sensors installed on the dam structure and the surrounding environment. These sensors measure parameters such as water levels, flow rates, pressure, structural integrity, and seismic activity. This real-time data collection ensures that any changes or anomalies are detected immediately. It includes advanced analytical tools that allow users to analyze the collected data in detail. Predictive maintenance algorithms help in forecasting potential issues before they become critical, enabling proactive maintenance and reducing the risk of failures.

The software provides easy-to-understand and customizable dashboards that offer visual representations of key data points and trends. These dashboards make it easier for users to interpret complex data, identify patterns, and make informed decisions quickly. In addition to monitoring dam-specific parameters, the *AEM Dam Safety* software integrates weather forecast data. It helps in predicting the impact of weather conditions on dam operations, allowing for a more effective response. Graphs, charts, and 3D models are used to display information such as water levels, structural health, and weather conditions.

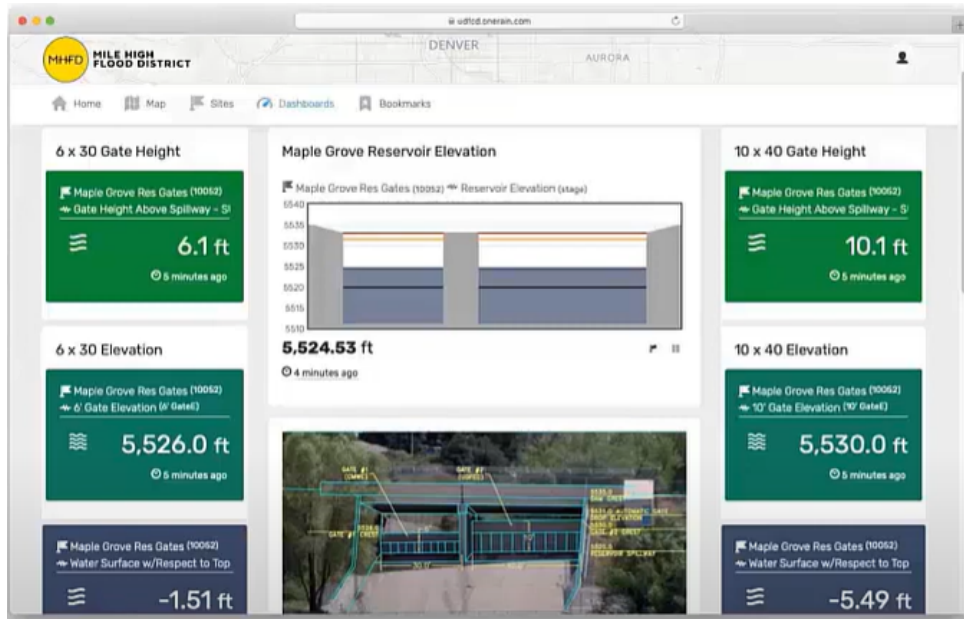


Figure 3.7: AEM Dam Safety dashboard [9]

The system is equipped with automated alert mechanisms that notify users of any significant changes. These alerts can be customized based on user preferences and can be delivered through various channels such as email, SMS, or in-app notifications.

AEM Dam Safety software securely stores all collected data, enabling historical analysis and long-term trend evaluation. Users can access historical data to study past events, understand seasonal variations, and improve overall dam management strategies.

The software helps ensure compliance with regulatory requirements by providing tools for generating detailed reports and documentation. These reports can be customized and exported in various formats to meet the needs of technical and non-technical audiences. The intuitive design and easy navigation allow users to quickly access the information they need and perform their tasks efficiently.

3.3 Related Work Discussions

The application of monitoring dashboards in engineering and various sectors has seen significant advancements, showcasing the integration of cutting-edge technologies to enhance system monitoring, safety, and performance. Through an analysis of existing tools and methodologies, we have gained valuable insights that have influenced the prioritization of features for our application.

Feature	<i>Dam360</i> [23]	<i>VDV</i> [24]	<i>ARMS4Dams</i> [7]	<i>Telnet</i> [25]	<i>AEM</i> [9]
Configurable Dashboards	✓	✓	✓	✓	✓
Customizable Alerts and Alarms	✓	✓	✓	✓	✓
Route Inspections Descriptions	✓	✓	×	×	✓
Automatic Overview Reports	✓	✓	✓	✓	✓
Offline Collection of Data	✓	✓	✓	✓	✓
Online Collection of Data	✓	✓	✓	✓	✓
Real-time Monitoring	✓	✓	✓	✓	✓
Predictive Maintenance	✓	✓	✓	✓	✓
Centralized and Secure Cloud-based Storage	✓	✓	✓	✓	✓
Users Access and Permissions	✓	✓	✓	✓	✓
Open-Source Project	×	×	×	×	×

Table 3.1: Comparative analysis of related work features

The reviewed tools and methodologies underscore the importance of real-time monitoring, diverse data visualization, and the integration of predictive analytics. These elements are critical in enhancing the safety and performance of dam systems. The integration of cloud technologies, as seen in *Dam360*, highlights the benefits of reducing data input errors and improving data reliability. Additionally, the user-friendly interfaces and real-time alert mechanisms in *AVEVA System Monitor* and *ARMS4Dams* illustrate the necessity of intuitive data presentation and timely intervention capabilities.

In developing our web application, these insights serve as a guiding framework. We aim to incorporate real-time monitoring and simulation capabilities to enhance dam safety measures. By exploring different methodologies for data visualization and analysis, we strive to create an intuitive and effective monitoring solution that addresses the needs of dam safety and performance management. Furthermore, our application integrates all the features identified as essential in the existing solutions. As depicted in the comparative table 3.1, our tool includes all the features analyzed. Our solution incorporates configurable dashboards, customizable alerts and alarms, route inspection descriptions, automatic overview reports, real-time monitoring, and responsive access. Additionally, it features offline and online data collection, centralized and secure cloud-based storage, user access and permissions, and predictive maintenance. This comprehensive approach ensures that our tool meets the highest standards of

functionality and usability in the field of dam safety management. A key focus of our application is ensuring that data visualizations are simple and easy to understand. By providing clear and intuitive graphical representations of complex data, users can quickly grasp critical information and make informed decisions. This approach is designed to enhance user experience and facilitate efficient decision-making processes.

This comprehensive understanding of existing tools and methodologies not only informs our application development but also positions us to contribute to the ongoing advancements in monitoring dashboards. By leveraging the strengths and addressing the limitations of current systems, our tool aims to provide a robust and user-friendly solution for dam safety and performance monitoring.

Furthermore, our application is designed to provide transparency, flexibility, and community-driven improvements through an open-source approach. By making the source code available to the public, we encourage collaboration, allowing developers and stakeholders to contribute to the project and adapt it to their specific needs. This open-source approach ensures that our application remains at the forefront of technological advancements and industry best practices, while also fostering a community dedicated to improving dam safety and monitoring. Another important feature we aim to develop is the presentation of a 3D visualization of the dam from various perspectives, such as the influence of temperature on the dam's behavior.

In summary, our application aims to fulfill all the critical features identified in the review of existing tools, ensuring a robust and comprehensive solution for dam safety management. This integration enhances monitoring capabilities, improve data reliability, and facilitate effective decision-making, ultimately contributing to the overall safety and efficiency of dam operations.

4

System Design: Insights Across Development Phases

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In this chapter, we will focus on the conceptualization of the system design, from the stage of gathering the specific requirements of the solution and the data that would support it, to the implementation of the final version of the dam monitoring dashboard.

The methodology presented in the following paragraphs serves as a guiding framework for my work, ensuring a systematic approach to developing a visualization solution for my case study. Each stage had been carefully addressed to meet the specific needs of a dam monitoring dashboard.

The article "Design Study Methodology: Reflections from the Trenches and the Stacks" [26] by Michael Sedlmair, Miriah Meyer, and Tamara Munzner is a foundational paper in the field of visualization design studies. Its primary focus is to provide a structured methodology for conducting visualization design studies while addressing practical challenges and solutions encountered during real-world projects.

A design study [26] is defined as a collaborative effort between visualization researchers and domain experts to create custom visualization solutions tailored to specific real-world problems. To guide this process, the authors propose a nine-stage methodology that takes researchers from project initiation to evaluation. These stages are:

1. **Learn:** Deeply understand the domain, stakeholders, and their problems. (Background research and related work are explored in this stage)
2. **Winnow:** Identify and prioritize opportunities where visualization can make the most impact.
3. **Cast:** Select collaborators, define the domain problems, and establish the project scope.
4. **Discover:** Explore the data, workflows, and processes within the domain. (Requirement Gathering and Data Cleaning and Processing occur here)
5. **Design:** Develop prototypes tailored to the needs of the domain experts. (This phase involves the design of both low-fidelity and high-fidelity prototypes)
6. **Implement:** Build functional visualization systems based on the prototypes.
7. **Deploy:** Deliver the finalized system for use in the domain environment.
8. **Reflect:** Assess the lessons learned, challenges faced, and project outcomes.
9. **Write:** Document and communicate findings, methodologies, and results effectively.

4.1 Requirement-Gathering

The Requirement-gathering stage forms a crucial foundation for the development of a dam monitoring dashboard, aligning the system's technical objectives with stakeholder needs and data availability. This section integrates Tamara Munzner's Design Study Methodology [26] to identify the requirements, ensuring that the project is tailored to address domain-specific challenges effectively.

The data for this project is sourced from LNEC database. The data attributes are categorized into four key domains:

- **Structural:** Includes metrics such as dam height, length, and base width, critical for understanding the physical properties of the dam.

- **Hydrological:** Compasses reservoir levels, inflow and outflow rates, and total capacity, providing information on water dynamics.
- **Environmental:** Includes precipitation, evaporation, and temperature data, helping to identify external factors affecting the reservoir.
- **Geotechnical/Geological:** Focuses on seismic activity attributes, such as earthquake magnitude and ground acceleration, which are vital for understanding seismic risks.

A structured overview of these datasets prioritizes the most relevant attributes for the dashboard's visualizations, ensuring they align with the system's objectives, as described in Section 4.7.1.

Some of the key tasks for the dashboard are defined based on the client's needs. These tasks aim to provide actionable insights and answer critical questions, such as identifying maximum and minimum reservoir levels, analyzing the relationships between water levels and temperature, and comparing ground acceleration trends before and after seismic events. By addressing these points, the dashboard supports decision-making processes for dam safety and operational efficiency.

4.2 Global Sitemap

In this section, we explore the Seismic and Structural Health Monitoring for Dams (SSHM4Dams) global sitemap, focusing on my main contribution: the dam monitoring dashboard. The sitemap serves as a blueprint for the website's structure, showcasing all functionalities available to users.

The overall structure includes general sections such as Home, Map, About, Team, Publications, and Data-Sharing. These sections provide essential information about the project and facilitate dam analysis.

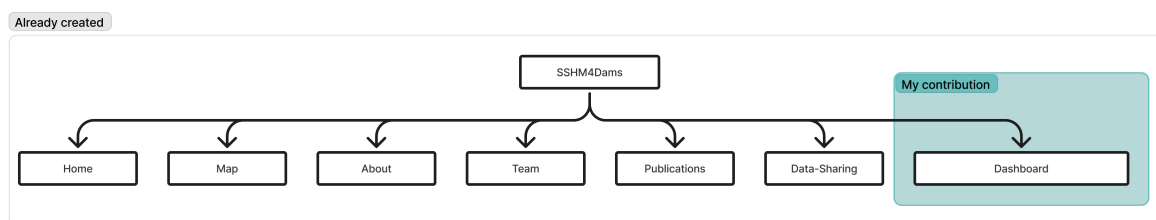


Figure 4.1: Overview website sitemap

The following figure illustrates the logical organization of all necessary components. This organization is fundamental for facilitating navigation and enhancing the user experience.

The dashboard, which is my primary contribution, is a specialized section designed to address the specific needs of dam monitoring. It is organized into several key components:

1. Visualizations

- **Dam 2D Schematic Representation:** This includes accelerograms and their Fast Fourier Transform (FFT) analysis, providing insights into the dam's structural responses.
- **Overall Analysis:** Features vibrational mode representations, displacement time series plots, and double-line charts to comprehensively view the dam's behavior.

2. Sidebar

- **Seismic Timeline:** Displays a chronological sequence of seismic events, which aids in historical analysis.
- **Geo-localization Map:** Provides a spatial representation of seismic activity, improving the geographical context.
- **Earthquake Details Table:** Offers detailed information on individual seismic events, supporting in-depth analysis.

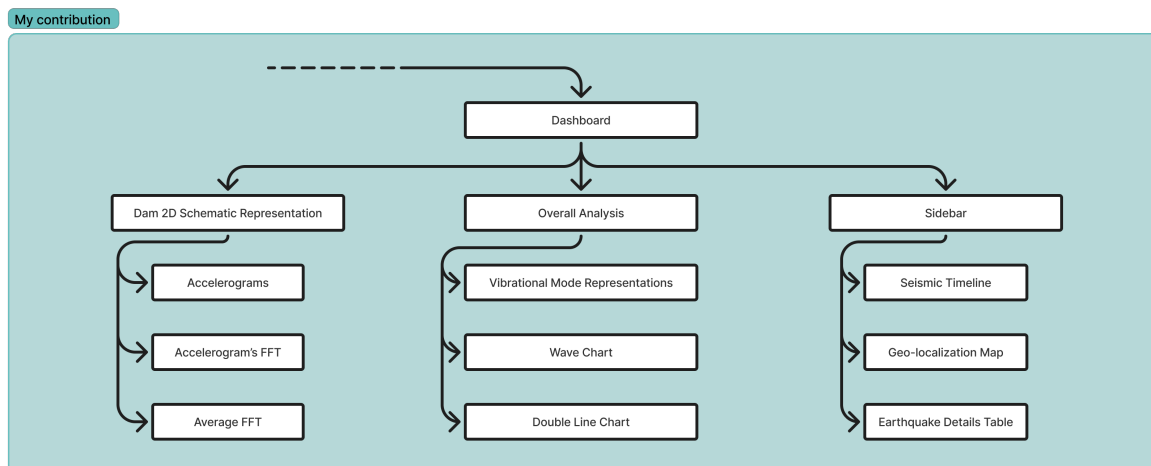


Figure 4.2: Dam monitoring dashboard sitemap

In summary, the sitemap and my contributions to the dashboard are integral to the project's success, providing a structured and effective tool for dam monitoring and decision-making.

4.3 Data Cleaning and Processing

The data cleaning and processing phase ensures that the datasets provided by LNEC are properly formatted, structured, and ready for visualization. This step is critical in maintaining data integrity and accuracy, facilitating analysis for dam monitoring and safety tasks.

The provided datasets include essential parameters such as water level measurements, temperature records, and seismic acceleration data. These datasets span from December 1974 to November 2024, ensuring a comprehensive historical analysis.

To begin, we identify the key attributes available within the datasets. Several derived attributes are then computed to enhance the dataset's analytical capabilities, including:

- Monthly and Yearly Water Level Averages;
- Monthly Minimum and Maximum Temperature Averages;
- Daily Temperature Average;
- Daily and Monthly Thermal Amplitude;
- FFT on Acceleration Data.

To better structure the dataset, each identified attribute is classified according to its type, scale, field name, and semantics. This ensures clarity in data interpretation and facilitates their integration into visual representations. Following that, the data cleaning process is completed. Since the provided datasets contain no significant missing values, imputation or row removal is not required.

Additionally, data formatting is essential to ensure compatibility with visualization tools such as D3.js. Therefore, all datasets must be converted into standardized formats like JSON to facilitate seamless integration into the dashboard. It is also important to highlight that data has been processed locally before being migrated to a centralized database.

To complete this phase of the project, the processed data supports various analytical tasks, including:

- Identifying correlations between water levels and temperature fluctuations.
- Detecting patterns in seismic activity and their impact on dam stability and integrity.
- Analyzing seasonal trends in water level variations.
- Distinguishing seismic event acceleration peaks from regular operational or ambient acceleration signals.
- Identifying natural vibration mode frequencies using FFT analysis of sensor data.

This data cleaning and processing approach ensures that the dam monitoring dashboard operates with high-quality data, providing accurate information for users.

4.4 Visualization Sketch

This section details the selected attributes and the corresponding visual encoding strategies, demonstrating how the dashboard enables users to perform various tasks and supports the engineers' decision-making process. The first sketches of the dam monitoring dashboard were developed in collaboration with LNEC following data processing and cleaning, as documented in Section 4.7.2.

4.4.1 Idioms Sketch

To effectively analyze dam behavior during seismic events or under normal operation conditions, it is essential to implement appropriate visual encoding techniques that transform raw data into meaningful insights. Multiple visualization approaches were incorporated, each customized to different types of analysis required for monitoring dam conditions. This section details the visual encoding strategies chosen for the dashboard, explaining how each representation aids in answering critical research questions related to dam safety, seismic activity, and environmental influences.

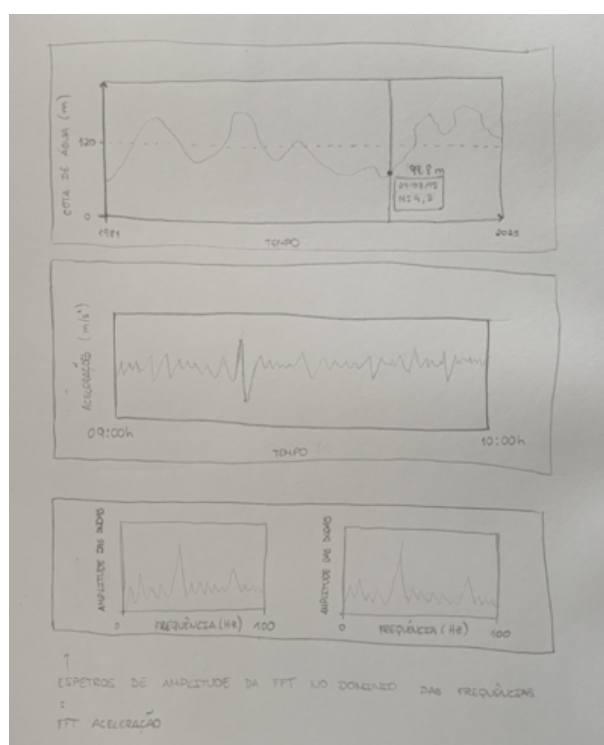


Figure 4.3: Idioms sketch

The dashboard incorporates various attributes, mapping them to appropriate visualization techniques that allow users to explore patterns and correlations effectively. One of the most important variables for dam monitoring is the water level, which fluctuates due to environmental factors, inflows, and operational

controls. To represent these variations over time, a line chart is used, with the X-axis representing time and the Y-axis showing water level in meters. The visualization includes lines and dots to mark data points, while color encoding improves readability. Seismic events are highlighted with vertical reference lines, enabling users to identify their occurrence quickly. Additionally, hover interactions provide precise water level values at selected points, making it easier to analyze the correlation between long-term reservoir level trends and seismic activity.

In addition, seismic acceleration data is visualized to evaluate dam responses during earthquakes. Measurements from different monitoring points on the structure are plotted using event-specific line charts, known as accelerograms. The X-axis displays time relative to the event, while the Y-axis measures acceleration in m^2/s . Users can select a monitoring point from a 2D dam representation, dynamically updating the graph to display acceleration data for that specific location. By default, the central upper monitoring point is pre-selected, but users can also compare data from multiple locations. To further assess seismic effects, FFT analysis is applied to acceleration data, converting time-domain information into the frequency domain. The resulting frequency spectrum is visualized using a line chart, where the X-axis represents frequency (Hz) and the Y-axis shows acceleration amplitude. Two FFT graphs are displayed side by side, comparing data before and after the seismic event. Color-coded peaks highlight frequency shifts, allowing users to identify potential structural changes. By integrating these visualization techniques, the dashboard provides an interactive and user-friendly approach to dam monitoring, supporting engineers and decision-makers in assessing risks and ensuring structural integrity.

4.4.2 Visual Encoding

Variable	Data Type	Visualization Method
"time", "water_level", "temperature"	Quantitative	Double-Line Chart (Marks: lines, dots; Channels: area, color, size)
"vibration_data", "mode"	Quantitative	Dam Vibration Mode Analysis (Marks: lines, dots; Channels: color, size)
"selected_dam", "sensors_location"	Categorical	Clickable Image (2D Dam Representation) (Marks: dots; Channels: position, color, size)
"time", "acceleration_Px"	Quantitative	Line Chart (Marks: lines, dots; Channels: area, color, size)
"time", "acceleration_Px"	Quantitative	Acceleration FFT Spectrum Chart (Frequency vs. Amplitude) (Marks: lines, dots; Channels: area, color)
"time", "acceleration"	Quantitative	Average FTT Chart (Line Chart) (Marks: dots, lines; Channels: position, color)

Table 4.1: Variable encoding strategy

To ensure an effective and intuitive representation of seismic and hydrological data, various attributes are mapped to specific visualization techniques. This structured approach ensures that visualization methods align with real-world dam monitoring needs.

4.4.3 Dashboard Sketch

To determine the most effective visualization and interactive techniques for seismic and hydrological data, different sketches exploring alternative strategies, layouts, and functionalities were developed before proceeding with the final dashboard solution. Three distinct dashboard sketches were designed to explore various interaction and filtering methodologies for dam monitoring data. Each sketch incorporates time-series visualizations of critical parameters, a 2D schematic representation of the dam with interactive monitoring points, and various acceleration visualization methods as core visualization content.

However, the key difference is the functionality of the sidebar menu: one focuses on timeline-based filtering for historical trend analysis, another emphasizes geospatial filtering for site-specific data selection and spatial variation assessment, and the third provides a highly customizable hybrid filtering system that includes a dedicated event selection table, allowing users to sort events by magnitude, distance, or date, catering to a wide range of analytical needs. Throughout the sketching process, several uncertainties arose regarding the sidebar and its functionality. The sidebar needed to balance ease of navigation, data filtering options, and accessibility to key monitoring parameters. However, its structure remained dependent on feedback from LNEC engineers, as their experience was crucial in determining the most practical configuration.

For reference, all three dashboard sketches have been included in Appendix A.

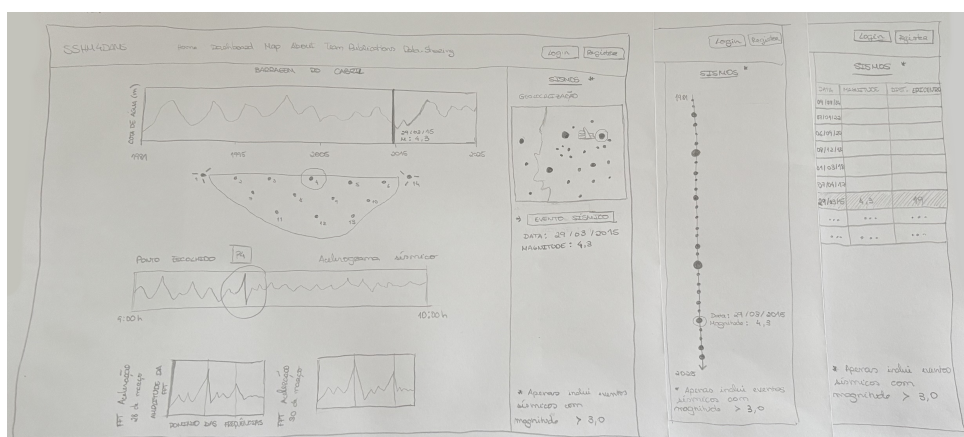


Figure 4.4: Sidebar dashboard sketches

Before proceeding to the low-fidelity prototype, further discussions were necessary to refine:

- The organization of filtering options (e.g., should severity, date, or location group events?).
- The level of customization available to users (predefined vs. user-defined dashboards).
- Optimal placement of key interactions to ensure usability for dam monitoring teams.

Following these discussions, the feedback from LNEC engineers described in Section 4.7.3 had been integrated into the design process. Based on this feedback, the most suitable layout from the three sketches was selected, forming the foundation for the low-fidelity prototype.

4.4.4 Answering questions

A series of tasks within the dashboard allows us to explore key questions. By analyzing seismic events, temperature variations, water levels, and acceleration data, the dashboard provides essential comparisons and conclusions about dam conditions and safety. Visualizations such as acceleration records, FFT, and historical trends can help us better understand the dam's structural behavior and its response to environmental and seismic influences.

How do seismic events influence dam stability based on acceleration measurements?

By analyzing acceleration data from multiple points on the dam before and after seismic events, we can assess changes in vibrational behavior and identify potential structural weaknesses affecting dam stability.

The dashboard offers tools for visualizing acceleration time series and performing FFT analysis to examine frequency-domain characteristics. Comparing acceleration amplitudes and dominant frequencies before and after an earthquake evaluates how the seismic event affected the dam.

Key analyses and visualizations:

- Acceleration time series recorded at different monitoring points.
- FFT analysis comparing acceleration amplitudes from the day before and the day after the seismic event.
- Identification of frequency shifts and amplitude variations offers an overview of the structural response to the seismic event.

Is it possible to identify any trend or relationship between the gallery (or its elevation) and the amplitude of observed accelerations?

Dam gallery elevation strongly influences the magnitude of recorded accelerations. Therefore, lower galleries tend to experience lower acceleration amplitudes compared to higher-elevation galleries, which are more exposed to external forces.

The dashboard allows users to compare acceleration amplitudes recorded in galleries at different elevations. By selecting specific points on the 2D dam representation, users can compare the corresponding FFT graphics and analyze the differences in observed amplitudes. Plotting these acceleration data against gallery elevation helps identify how acceleration levels vary with structural positioning.

Key analyses and visualizations:

- Visualization of acceleration amplitudes (FFT Analysis) for gallery points at different elevations.
- Establish a correlation analysis between gallery elevation and observed accelerations and amplitudes.
- Identification of dominant acceleration and amplitude trends relative to gallery depth within the dam.

Is there a pattern between the accelerations recorded at opposite points of the dam structure?

Comparing acceleration records from opposite points of the dam (e.g., 1 and 14, 2 and 6) can reveal patterns in seismic wave propagation through the structure. If acceleration amplitudes and dominant frequencies are similar at opposite points, it suggests a uniform seismic wave distribution across the dam.



Figure 4.5: 2D representation of monitoring points on the dam

The dashboard enables side-by-side analysis of the acceleration records, allowing direct comparison of seismic response at different structural points.

Key analyses and visualizations:

- Seismic acceleration time series recorded at opposite monitoring points.
- FFT analysis of accelerations at the corresponding locations.
- Identification of similarities or discrepancies in vibrational responses at opposite dam points.

These analyses provide information about the dam's response to seismic activity and environmental influences, helping to ensure its integrity and stability.

4.4.5 Seismic events and Dam Stability Storyboard

This section represents how seismic events influence dam stability based on acceleration records. The storyboard outlines the sequence of analyses available in the dashboard, allowing a step-by-step examination of the dam's response to seismic activity. As Rachel Krause said, a storyboard in User Experience (UX) [27] communicates a story through images displayed in a sequence of panels that chronologically map the main events of the story. Through various data visualizations, the storyboard connects seismic events with acceleration measurements, helping to identify potential structural changes or instabilities caused by earthquakes. For reference, the storyboard figures have been moved to B.

These figures illustrate how different features and visualization methods dynamically adapt to user interactions. When a seismic event is selected, the sidebar highlights it by encircling its corresponding point on the seismic event timeline and displaying an information box. Once selected, a vertical bar appears in the Temperature and Water Level Double-Line chart, marking the moment the event occurred and showing the magnitude and date of the seismic event. This visualization allows users to compare the water levels and temperatures before and after the earthquake. Additionally, users can interact with the graph by zooming in and out to adjust the time interval being analyzed.

Regarding dam monitoring points and additional data, a 2D visual representation of the dam displays the locations of the sensors. When a specific sensor point is selected, two additional line graphs appear below, providing detailed acceleration measurements from that location. In the seismic acceleration record, the acceleration time series for one hour is displayed, with the peak acceleration value highlighted. Users can adjust the time interval for analysis by zooming in and out. Additionally, the last two graphs display FFT analysis, where frequency domain transformations of acceleration data highlight the moments when significant amplitude variations were recorded before and after the seismic event, helping to identify structural changes.

The final storyboard representation consolidates all these interactive elements into a single view. It ensures that each step, from selecting a seismic event to analyzing acceleration data and frequency transformations, flows logically, helping engineers quickly detect anomalies, evaluate trends, and assess structural stability over time.

The key elements included in the storyboard are the following:

1. **Seismic Event Timeline** – A chronological view of recorded seismic events, highlighting the selected earthquake for analysis.
2. **Water Level Time Series** - A graph that depicts water level variations over time, allowing correlation with seismic occurrences.
3. **Dam Monitoring Points** – A schematic representation of the dam structure, indicating the locations of acceleration sensors.

4. **Seismic Acceleration Record** – Time series data of acceleration measurements from a selected monitoring point before, during, and after the seismic event.
5. **FFT analysis** - A frequency domain transformation of acceleration data comparing pre-earthquake and post-earthquake conditions to detect changes in vibrational behavior.

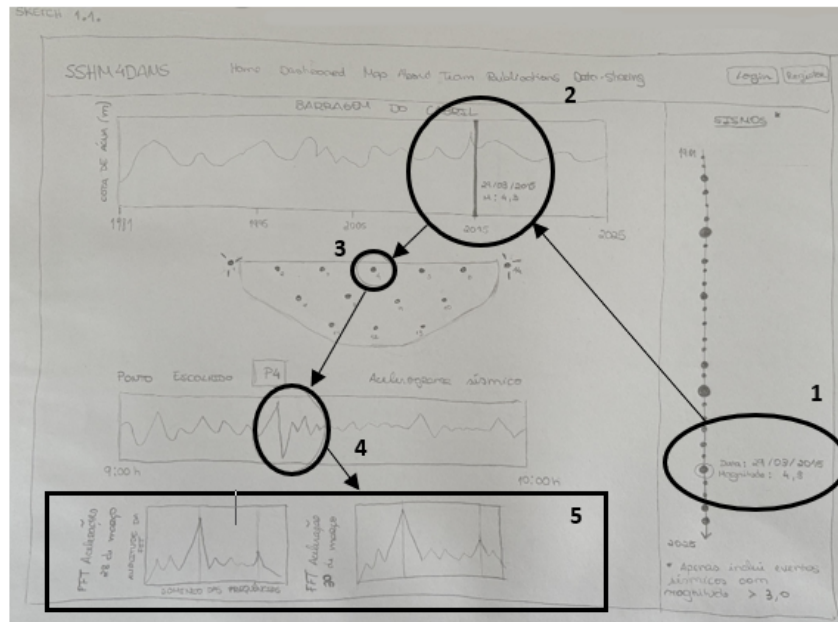


Figure 4.6: Storyboard illustrating how seismic events influence dam stability based on acceleration measurements

Following this structured approach, the storyboard offers an intuitive way to assess the dam's response to seismic activity. The interactive visualizations facilitate real-time monitoring and contribute to the evaluation of dam conditions. As detailed in Section 4.7.3, feedback from LNEC engineers was necessary to refine these visualization strategies, ensuring effective data representation and usability before developing the low-fidelity prototype.

4.5 Low-fidelity Prototype

A low-fidelity prototype [28] is an early-stage representation of a digital interface, emphasizing structure, layout, and functionality rather than visual details. These prototypes are often used in the design process to gather feedback and refine usability before investing time in high-fidelity design. This prototype was designed to map out the key functionalities and user interactions, ensuring the interface meets the LNEC requirements.

At the top, a navigation menu provides access to different sections, such as the home page, dashboard, maps, team information, publications, and data-sharing. A login and register button suggests

user authentication for personalized access, resulting in distinct permissions. On the right-hand side, users can select a seismic event through three different methods: geolocation, a table displaying magnitudes and epicenter distances, or the seismic event timeline, which organizes recorded earthquakes chronologically. Alternatively, users can directly select a specific date for analysis. Once an event is chosen, an information box appears, enabling a focused examination based on parameters such as epicenters' distance, magnitude, and time of occurrence.

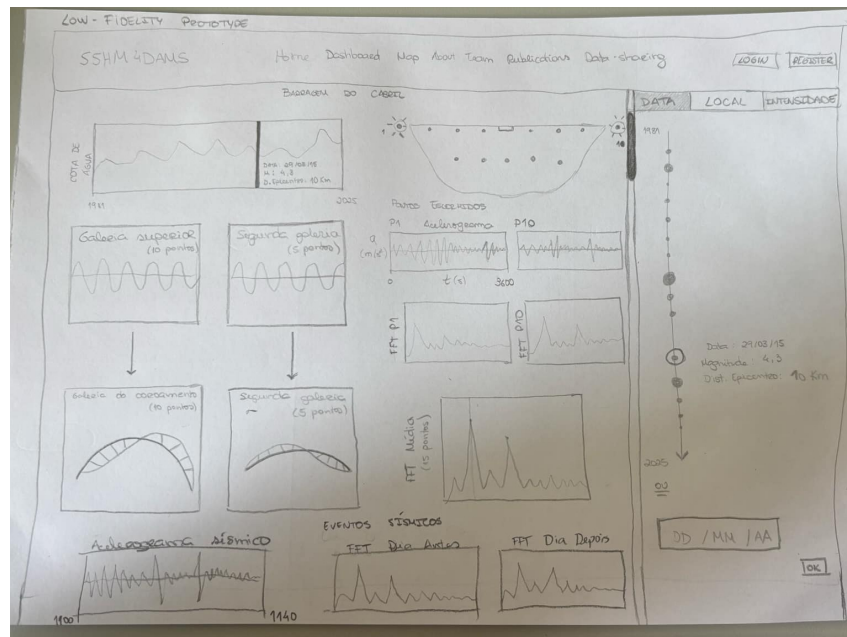


Figure 4.7: Dam monitoring dashboard low-fidelity prototype

In the central section, a water level time series graph shows variations in water elevation over time, allowing users to correlate seismic events with changes in water level. A 2D schematic representation of the dam also displays monitoring sensor locations. The interface includes the crest and second gallery sections, each with multiple monitoring points. Below these, seismic accelerograms and vibrational modes are presented, aiding structural behavior analysis. Corresponding to selected monitoring points, one or two seismic accelerograms and FFT graphs appear under the dam schematic. An additional FFT graph displays the average response of all sixteen sensors, providing a comprehensive vibrational assessment.

Reflecting the selected monitoring points, one or two seismic accelerograms appear along with their respective FFT graphs. Additionally, an FFT graph displaying the average response of all sixteen sensors is shown, providing an overall assessment of the dam's vibrational behavior.

By scrolling down, users access the seismic events section, which presents a zoomed-in accelerogram focusing only on the event under analysis. This section also includes two FFT graphs, one for the day before and another for the day after the event. These visualizations help engineers assess whether

any structural damage occurred due to the seismic activity by comparing changes in frequency response patterns.

The prototype highlights interactivity, allowing users to zoom in on specific time intervals, compare acceleration responses across different dam sections, and track structural changes through frequency analysis. As documented in Section 4.7.4, feedback from LNEC engineers contributed to refining key aspects of the prototype, including improvements to time-series analysis, frequency tracking, and interactive visualization strategies. By creating this low-fidelity prototype, the design process benefits from early validation and iterative improvements, leading to a more user-centered and functional dashboard.

4.6 High-fidelity Prototype

The high-fidelity prototype was designed to improve the analytical capabilities and user experience. The Water Level Time Series graph now features a dual-line visualization, allowing direct comparison of water levels and temperature variations. The seismic acceleration graph's time interval dynamically adjusts to event magnitude, ensuring comprehensive analysis of larger earthquakes and aftershocks, which have significant structural implications. These refinements significantly enhance the prototype's ability to support dam monitoring, seismic assessment, and structural safety analysis. By incorporating expert recommendations, the final dashboard version offers greater precision, improved data visualization, and a more intuitive interface for LNEC engineers and all other users.

The high-fidelity prototype was presented for engineering review, and no further improvements were identified. However, it was suggested to display only one accelerogram chart for each 2D clickable point, instead of showing both the pre- and post-earthquake accelerogram charts. As a result, the development process progressed toward the implementation of the final dashboard solution.

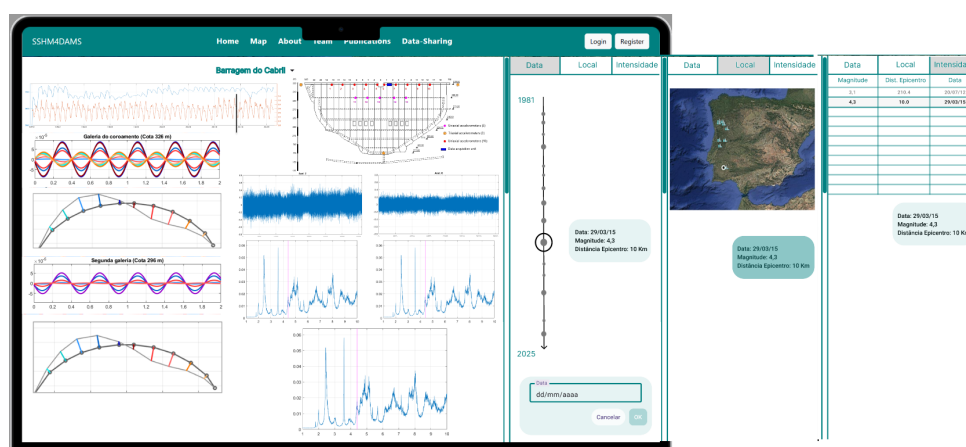


Figure 4.8: Dam monitoring dashboard high-fidelity prototype

4.7 Feedback from LNEC

Throughout the development of the dam monitoring dashboard, continuous feedback from engineers at LNEC played an important role in improving the final solution. This chapter presents the feedback during different phases of development.

The feedback process began with early discussions to define requirements, ensuring that the proposed solution met the real needs of dam monitoring engineers. Analyzing the engineers' suggestions across these phases led to several improvements in the dashboard solution.

4.7.1 Introductory Client Meeting

The initial client meeting was essential to understand the expected solution and align the project's objectives with the client's requirements. In this meeting, the client elaborated on their specific needs and outlined the key features that the dam monitoring dashboard should provide. This discussion refined the focus of the dashboard and ensured it would effectively address real-world challenges related to dam monitoring and safety.

One of the crucial outcomes of this meeting was the provision of datasets by LNEC. After reviewing the initial requirement-gathering document, he provided access to relevant data related to the Cahora-Bassa dam.

The datasets collected during this phase include:

- **Acceleration data:** Records of seismic activity, including ground acceleration metrics, which are critical for assessing the structural integrity of the dam under seismic events.
- **Water Level data:** Measurements of reservoir levels, essential for monitoring hydrological conditions and ensuring operational efficiency.
- **Temperature data:** Environmental temperature records that explain the influence of external factors on water levels and structural stability.

These datasets undergo processing and cleaning to ensure that they are properly structured for visualization and analysis.

4.7.2 Second Client Meeting

After processing and cleaning all the data provided, we held a new meeting with the client, where we designed the first sketch of the solution. As we can observe in 4.9, the client highlighted key points that must be incorporated into the solution. These requirements focus on comprehensive data analysis and monitoring of the dam's condition in several areas. A major objective is temporal monitoring,

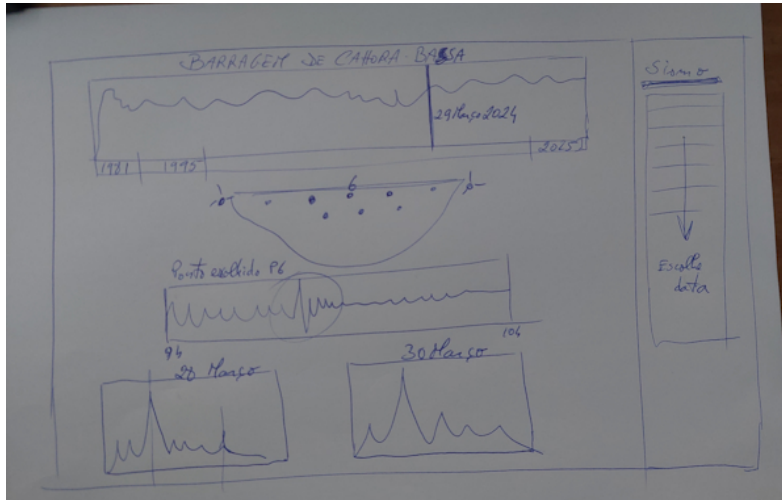


Figure 4.9: Client solution sketch

where the dashboard should include a detailed timeline, allowing data analysis from 1981 to 2025 and an evaluation of the dam conditions over the years. The dashboard must also facilitate correlation between parameters, showing a clear relationship between water level, temperature, and seismic events, facilitating predictive analysis.

Furthermore, the features include comparing measurement points, specifically acceleration data at different points in the dam, such as P6, which was highlighted in the sketch. Another important requirement is frequency pattern analysis, which demands the processing of acceleration data using the Fast Fourier Transform (FFT) to identify patterns, outliers, and structural oscillations.

Additionally, the client emphasized the inclusion of a dedicated section displaying seismic events and their correlation with other monitored parameters. Users should be able to select a specific seismic event, by magnitude or date, and review the dam's conditions before and after the selected event.

This client sketch serves as the starting point for developing the visualization sketches, ensuring that the client's requirements are effectively met.

4.7.3 Visualization Sketches Feedback

During this development phase, several design challenges emerged, particularly regarding the sidebar's structure and usability, and user customization of dashboard content. To address these issues, additional feedback was collected from LNEC engineers to ensure that the interface provides efficient navigation and facilitates interaction with critical data. Regarding the sidebar, LNEC recommended maintaining the three filtering options studied: severity, geolocation, and time-based. User customization remains predefined to ensure structured analysis, as the visualization order is critical.

A discussion also explored splitting the dashboard into two horizontal sections, accessible via scrolling.

This layout would allow users to monitor dam data across various periods, including days without seismic events, complementing the already studied approach of analyzing only seismic events and their impacts. Furthermore, it was suggested that one of the visualization's main focuses should be the dam structure's vibration modes. This would be achieved by studying accelerations in the crest gallery to gain insights into structural behavior.

Lastly, another key recommendation was the ability to simultaneously select two monitoring points in the 2D dam representation, instead of a single point as originally planned. This enhancement would allow for a comparative analysis of acceleration data between different locations, improving the understanding of seismic effects on the dam.

4.7.4 Low-Fidelity Prototype Feedback

To evaluate the dashboard's usability and clarity, I presented the low-fidelity prototype to three LNEC engineers. Their feedback contributed to refining the design and ensuring that the visualizations effectively conveyed critical information. The engineers evaluated the interface's intuitiveness and ease of understanding, providing key recommendations for improvement. One essential suggestion was to enhance the Water Level Time Series graph by introducing an optional dual-line visualization, allowing users to overlay temperature variations over time alongside water levels. This feature offers a broader environmental perspective on factors influencing the dam's behavior.

Lastly, the engineers recommended refining the seismic acceleration graph in the seismic event analysis section. They suggested dynamically adjusting the x-axis interval based on the magnitude of the selected earthquake, ensuring that aftershocks of higher magnitude events are adequately captured. These insights were crucial in improving the dashboard's analytical depth and usability, shaping the final high-fidelity prototype.

4.7.5 Discussion

This continuous collaboration enabled the identification and implementation of key improvements, such as enhanced data correlation features, improved comparative analysis tools, and more intuitive visualizations. The consistent incorporation of expert input not only increased the usability of the dashboard but also validated the design decisions across all phases.

Based on these evaluations and refinements, we conclude that the project is ready to advance to the implementation of the dashboard prototype. The iterative feedback process has laid a strong foundation for a solution that is both functional and user-centered.

5

Implementation

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In this chapter, we focus on the implementation of the final version of the dashboard, which is a demonstration of a proof of concept. This implementation highlights the practical applicability of the proposed architecture and shows how the tools developed can process real monitoring data, support decision-making, and provide an intuitive and interactive visualization environment for users.

5.1 Dam Monitoring Dashboard

The proposed solution involves the development of a dynamic, responsive, single-page web application dashboard for analyzing and visualizing data. This dashboard has been built using modern web development tools and frameworks, ensuring functionality and an intuitive user experience. Additionally, this project was integrated into the existing website ¹, enhancing its current capabilities. By incorporating our new dashboard, we aim to offer improved real-time data integration, advanced analytics, and a

¹<https://sshm4damswebapp.vercel.app/>

user-friendly interface for comprehensive dam monitoring.



Figure 5.1: Dam monitoring dashboard solution

5.1.1 Solution Overview

Our dam monitoring dashboard aims to integrate all critical features to ensure a robust and comprehensive solution for dam safety management. A standout feature of this solution is the configurable dashboard. Users can adjust the width of the dashboard content, allowing more space for the visualizations. While the number and order of elements shown on the dashboard remain fixed due to the importance of visual sequence for analysis and task completion, users can personalize the interface by hiding or showing the sidebar or by reducing its size. This component ensures that enough visualization space is available to facilitate important conclusions and support the decision-making process.

Throughout the implementation and conceptualization of the dashboard, we continuously received feedback from LNEC engineers regarding the intended use of this web application. Due to the unavailability of the necessary data for generating the visualizations, it became essential to select a dam for which we had the largest and most comprehensive dataset available to build a solid proof of concept. Given this context, the Cahora-Bassa dam was identified as the most suitable choice.

It is also important to note that some functionalities complementary to the dashboard's implementation were already developed. The user configuration and permission system, as well as the server infrastructure, were already in place. Therefore, the only remaining requirement was to develop methods to create and manage new data requests to the database. Additionally, the report generation feature had already been previously implemented and could be accessed through the "Map" tab at the top of

the website.

That said, it is important to emphasize that all visualizations included in the dashboard were selected based on the insights and requirements provided by the LNEC engineers. Each visualization was carefully chosen to be essential in supporting the decision-making process and in enhancing the understanding and identification of potential structural failures or risks. These visualizations aim to provide clear, intuitive, and informative perspectives on dam monitoring data, ensuring that the application meets the real-world needs of those responsible for dam safety. In summary, this comprehensive approach aims to significantly enhance monitoring capabilities, improve data reliability, facilitate effective decision-making, and contribute to the overall safety and efficiency of dam operations.

5.1.1.A Data Computation

As previously mentioned, all data is derived from acceleration, temperature, or water level measurements. Therefore, it was necessary to compute a significant portion of the data observed in this final solution. In this subsection, I explain how certain data were computed from acceleration measurements. All formulas used were verified and calculated by the engineers at LNEC. After collecting the acceleration data, it was necessary to use a Node.js module that allows us to compute the FFT of the accelerations for each sensor. Next, it is necessary to calculate the average spectrum of the FFT from all sensors to obtain the mean data for each frequency. This allows for the creation of a visualization that enables the identification of the most dominant frequencies, the natural frequencies of the dam, and the study of vibration modes associated with each of these frequencies. From this point onward, the setup is prepared to implement the data visualizations.

5.1.1.B Data visualizations / Dashboard Content

The dashboard integrates a diverse set of interactive and intuitive data visualization tools that together provide a powerful interface for dam monitoring and seismic analysis. From the Double-Line Chart, positioned at the top left of the dashboard, serves as a pivotal tool for analyzing the temperature and water level of the dam over time. The available data allowed for the study of these variables over a period exceeding fifty years, which made it necessary to implement resizable and configurable axes to analyze shorter time frames in greater detail. Using the mouse scroll, users can zoom in, with the axes adjusting automatically. Users can also click and drag to explore a different time period while maintaining the previously set level of zoom and detail. By hovering the mouse over the chart, crosshair lines appear along both axes (x and y), displaying labels with the observed values at specific points. This enables users to draw conclusions across different time periods, identifying trends and risks associated with fluctuations in the observed data values.

Another essential visualization method is the 2D schematic dam representation, which allows users to select sensors from which they wish to view acceleration data. When a selected point is clicked again, it is deselected. Users can select up to two points at a time. Once selected, a pair of visualizations is displayed to analyze the recorded accelerations and frequencies at each selected sensor. One of the visualizations in this pair is a seismic accelerogram. This accelerogram shows the acceleration recorded by the selected sensor over a time period of 3600 seconds (equivalent to one hour), around the moment of the seismic event or the selected date. The other visualization in this pair is a Line Chart that displays the FFT of the accelerations recorded during that same time window at the selected sensor. These visualizations support the same interactive features as the Double-Line Chart: zooming, mouse-over effects, and value labels, enabling a deeper understanding of the structural behavior.

To facilitate a more comprehensive analysis of accelerations and frequencies, an additional type of visualization is necessary. Maintaining the same design approach, we have the “Average FFT”, which is a Line Chart that allows the study of frequencies based on the average of all values recorded by all sensors. This enables the identification of natural frequencies and, consequently, the vibration modes of the dam. This chart also supports zooming in and out to examine the data at different levels of detail, and displays exact amplitude values for each frequency in the spectrum via mouse-over.

The final two visualizations are essential and complement each other. In each of these, it is possible to identify a likely amplitude value for each frequency per sensor. As shown in 5.1, Sensor 3, identified in green in both the Wave Chart and the Vibration Mode chart are the points that record the highest amplitude. With this set of two visualizations, it is only possible to change the vibration mode using the corresponding selector. In the Wave Chart, users can zoom in and out to compare the waves with the highest amplitude more precisely and to identify patterns such as symmetric and anti-symmetric modes. This multi-layered approach significantly enhances the ability to detect anomalies, assess risks, and make informed decisions. The following section explores complementary tools to support these analytical methods.

5.1.1.C Sidebar Timeline, Map, Table

The dynamic sidebar integrates different components to present data effectively to users, offering users a seamless interface to interact with data related to seismic events.

Each sidebar tab includes a shared section for dam selection and filtering capabilities via vertical range sliders. Selecting a dam focuses the application on seismic activities relevant to that specific infrastructure, providing critical insights into the seismic environment surrounding the dam. The sliders enable users to filter seismic events based on magnitude, distance, and date. These filters allow users to explore specific data subsets according to their interests or research needs.

The Timeline tab, as shown in 5.2(a), is designed to provide users with a chronological visualization

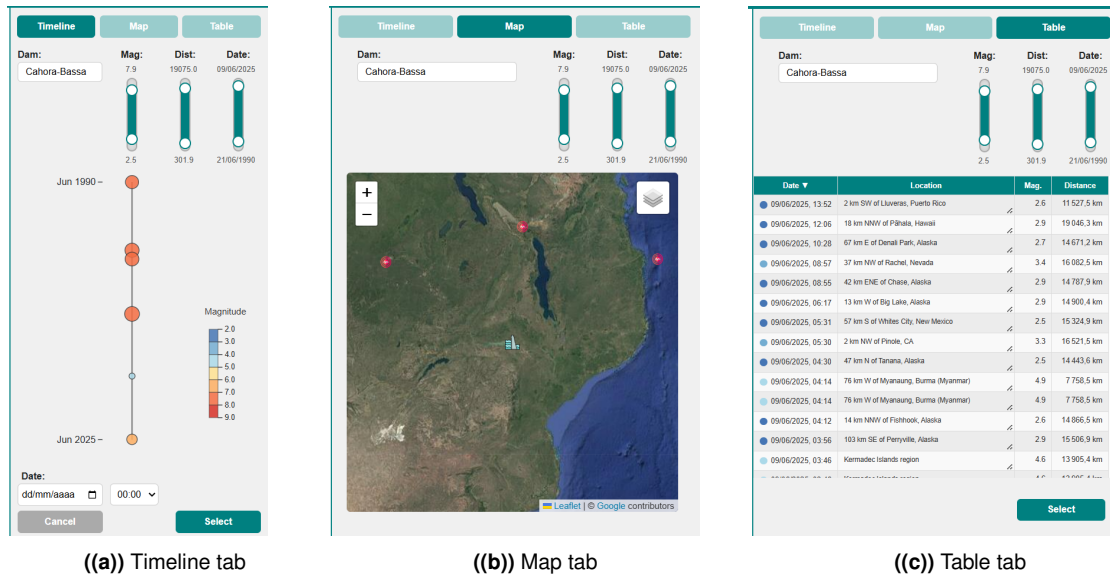


Figure 5.2: Comparison of sidebar tabs

of seismic activities, facilitating efficient temporal analysis of earthquake data. This visual representation enables quick assessments and historical insights, highlighting the occurrence and intensity of seismic events within a defined time frame. At the core of the Timeline tab is a dynamic interface where seismic events are represented as circles plotted along a vertical time axis. The size of each circle is proportional to the earthquake's magnitude, offering users an immediate visual cue to the event's relative strength—larger circles signify stronger seismic activity. Color is also used to represent magnitude, employing a D3 ordinal scale. A corresponding legend allows users to distinguish event magnitudes using both size and color as visual encoding channels.

The Timeline tab enables users to explore temporal patterns and frequencies of seismic events. By examining the distribution and clustering of these events graphically, users can identify trends such as peak activity periods or intervals of seismic calm. A notable functionality of the Timeline tab is the option to select a specific date for focused analysis. This feature allows users to investigate particular incidents or correlations with other datasets. When no data is available for the selected date, the date input option is disabled to maintain relevance and prevent user misunderstandings.

The Map tab (illustrated in 5.2(b)) leverages the Leaflet library to present a geographic visualization of earthquake data. It dynamically displays the physical locations of seismic events in relation to critical infrastructure such as dams, offering a spatial overview that is essential for assessing potential impacts. Each seismic event is marked with interactive icons, enabling real-time exploration. Markers reflect the location and magnitude of events, with clustering used to represent areas of high seismic activity. The clusters follow the same magnitude-based color scale used in other tabs. On mouse over, clusters display an animated tooltip with automatic scrolling, listing each event's date, location, and magnitude.

This spatial context allows users to understand relationships between seismic events and infrastructure at a glance. Overlay layers, such as seismic hazard maps, can be toggled for additional contextual information about risk areas. Users can click individual markers to retrieve detailed information about specific events, including magnitude, location, and related infrastructure. Zoom and pan features ensure a responsive and intuitive user experience crucial for both emergency response planning and long-term spatial analysis.

The Table tab (5.2(c)) offers a comprehensive, tabular view of earthquake data, ideal for users who require detailed, quantitative analysis. This view emphasizes structured exploration and supports in-depth examination through organized data presentation. Seismic events are listed in a detailed format, with fields such as date, magnitude, location, and distance. This structure ensures that all essential data is accessible in one place, enhancing both transparency and usability. A key feature of the Table tab is its ability to sort and filter data based on various attributes, including date, magnitude, and distance. These capabilities are particularly valuable for researchers and analysts who need to isolate specific datasets or uncover trends within extensive collections. The Table tab thus enables thorough comparative analysis. By providing a seamless transition from visual to numeric data, the Table tab supports data-driven decision-making, particularly for tasks that require detailed statistical evaluation.

A pivotal feature across all sidebar tabs is the consistent use of color to represent earthquake magnitudes. This color coding, based on magnitude intensity, enables quick differentiation between seismic events in every tab: Timeline, Map, and Table. Additionally, the use of circular representations remains consistent across tabs. Circle radius encodes earthquake magnitude, with larger circles signifying more intense events. This uniform visual language enhances user comprehension and ensures continuity in data representation across different visualization formats. Overall, the sidebar successfully integrates interactive and visualization elements, offering a holistic, user-friendly platform for analyzing earthquake data. It bridges geographic, chronological, and tabular dimensions, delivering a robust tool for both exploratory and analytical tasks.

5.1.2 Solution Architecture

Our single-page web application dashboard is designed to facilitate real-time data visualization. In our architecture, the user interacts with the dashboard through a web browser on their devices, performing tasks such as viewing data visualizations and analyzing the structural response of the dam.

The dashboard serves as the user interface, displaying various data visualizations and allowing users to interact with the data. Events generated by user actions, such as clicking on charts or adjusting configurations, are captured and handled by components within the dashboard. When a user interaction triggers a data request, the dashboard communicates with the backend server to handle data retrieval and updates. The server-side script processes the Application Programming Interface (API) requests,

interacts with the database server, and sends the necessary data back to the frontend. This database server serves as the primary data storage system, storing all the necessary data in a flexible format suitable for handling large volumes of structured data. Upon receiving a data retrieval request, the server-side script queries the database to fetch the required data. The fetched data is then sent back to the frontend via API endpoints. Once the data reaches the frontend, it is processed and filtered by the dashboard components to create meaningful visualizations.

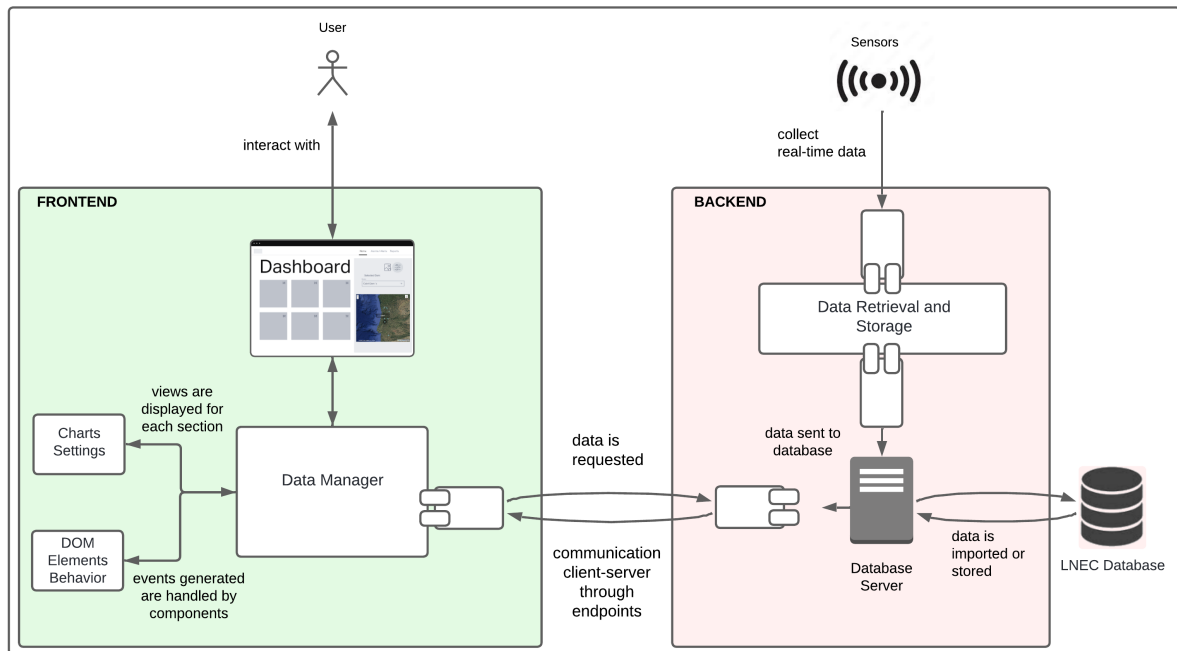


Figure 5.3: Web-application architecture solution diagram

In summary, our application follows the Model-View-Controller (MVC) architectural pattern. The MVC method separates the application logic into three different components. The Model manages the data insertion and loading. The View represents the user interface, with the dashboard acting as the view, displaying the data visualizations and handling user interactions. The Controller, represented as a Data Manager, handles user input and updates the view accordingly. This separation of concerns enhances the maintainability and scalability of our application.

5.1.2.A Data Manager

There is a module, represented as Data Manager in the previous figure, responsible for managing the data imported from a database or even just a file. The Data Manager module is crucial for handling various aspects of data management. It is responsible for filtering and processing the imported data to ensure its accuracy and relevance. Once the data is processed, the module creates data visualizations or labels to display this data effectively. Additionally, the Data Manager handles events generated by

user interactions with the dashboard, such as clicks, selections, and input changes. These events are processed, and the resulting data is displayed on the dashboard in real-time, ensuring that users have immediate access to updated information.

5.1.2.B Data Retrieval and Storage

This component represents the Model position in our MVC architectural pattern. This module manages the data, interacting directly with the database server to retrieve, update, and store data. In our solution, it recovered more recent data from sensors, represented this data, and stored it in the database. When needed, the Data Manager queries this component to import data. This real-time data handling mechanism ensures that the most up-to-date data is always available for analysis and reports.

All data computed and used in the program is stored and accessed via a database provider server, MongoDB, ensuring centralized and secure cloud-based storage. Since the data is not sensitive, there is no need to encrypt or protect it.

5.1.3 Solution Protocols and Frameworks

The implementation of this dynamic and interactive web application dashboard leverages several key tools and frameworks. It is important to remember that this project was built upon an existing website ², and therefore, some of the frameworks used were constrained by previous decisions. JSX (JavaScript XML), a syntax extension for JavaScript, is used in conjunction with React to describe the structure and layout of the web application. It allows developers to write HTML-like structures within their JavaScript code, ensuring the dashboard elements are correctly organized and accessible within React's component-based architecture. CSS (Cascading Style Sheets) is used to style the web application, defining the appearance of various HTML elements, including chart containers, lines, margins, and colors. This separation of style and content ensures maintainable and visually appealing code.

JavaScript remains the core programming language for implementing the dashboard's functionality and interactivity, handling event-driven programming and DOM (Document Object Model) manipulation to ensure dynamic updates to the user interface. React, a popular JavaScript library, is used to build the frontend interface. React's component-based architecture and declarative programming model facilitate managing and reusing User Interface (UI) components while ensuring that the dashboard responds smoothly to user actions, such as clicking on charts or adjusting configurations. D3.js is our selected JavaScript library for creating data visualizations. We chose D3.js over alternatives like Chart.js or Recharts primarily for its direct SVG manipulation capabilities, essential for our specialized dam monitoring visualizations, especially the 2D dam representation. It loads data from the MongoDB server,

²<https://sshm4damswebapp.vercel.app/>

processes and filters it, and generates visualizations such as line charts and bar charts. These visualizations are appended to the SVG (Scalable Vector Graphics) container, providing a clear and interactive representation of the data.

The backend of the application is implemented using JavaScript with Node.js, providing a robust and efficient environment for server-side operations. Node.js is particularly well-suited for handling asynchronous operations and managing a large number of simultaneous connections, which is crucial for real-time data applications. MongoDB is a NoSQL database that stores large volumes of data in a flexible, JSON-like format. It is well-suited for handling real-time data storage and retrieval, providing scalability and reliability. MongoDB ensures that the dashboard can efficiently manage and access the data needed for visualizations, even with large datasets. To ensure secure communication, all data transferred between the frontend and backend is encrypted using HTTPS, protecting data from interception. User authentication was already implemented to secure dashboard access using JSON Web Tokens for secure API communication. It ensures that only authorized users can access the dashboard and its data. By integrating these tools and frameworks, the web application dashboard provides a responsive, interactive, and visually appealing user experience, with real-time data handling and visualization capabilities.

5.1.4 User Interface

The user interface solution for the web application dashboard provides an intuitive and enjoyable experience for users, making it easy to interact with various data visualizations and functionalities. It is important to highlight that the target users are individuals with previous experience in data visualizations or dam dashboard fields, such as the engineers of LNEC. The process begins by directing users to the main dashboard, where they can select a dam either from an input selector or via geolocation on a map. Once a dam is selected, users are prompted to choose a seismic event or a specific date to view related data. The dashboard then displays various insights related to key dam monitoring parameters in a grid layout. Users can interact with these insights by clicking or hovering over each section to access more detailed information. For deeper analysis, users can expand certain visualizations to get a more detailed view.

Users consistently engaged with the double-line chart by hovering and zooming to pinpoint specific temperature or water-level values. This behavior highlights the importance of interactive chart elements in enabling precise data exploration. A common interaction involved users selecting individual sensors by clicking on sensor points. This action was primarily used to display sensor-specific acceleration data. The vibration mode selector was frequently utilized across various visualizations, including the vibration mode representation and the sensor wave chart. Users employed this tool to switch between different study modes.

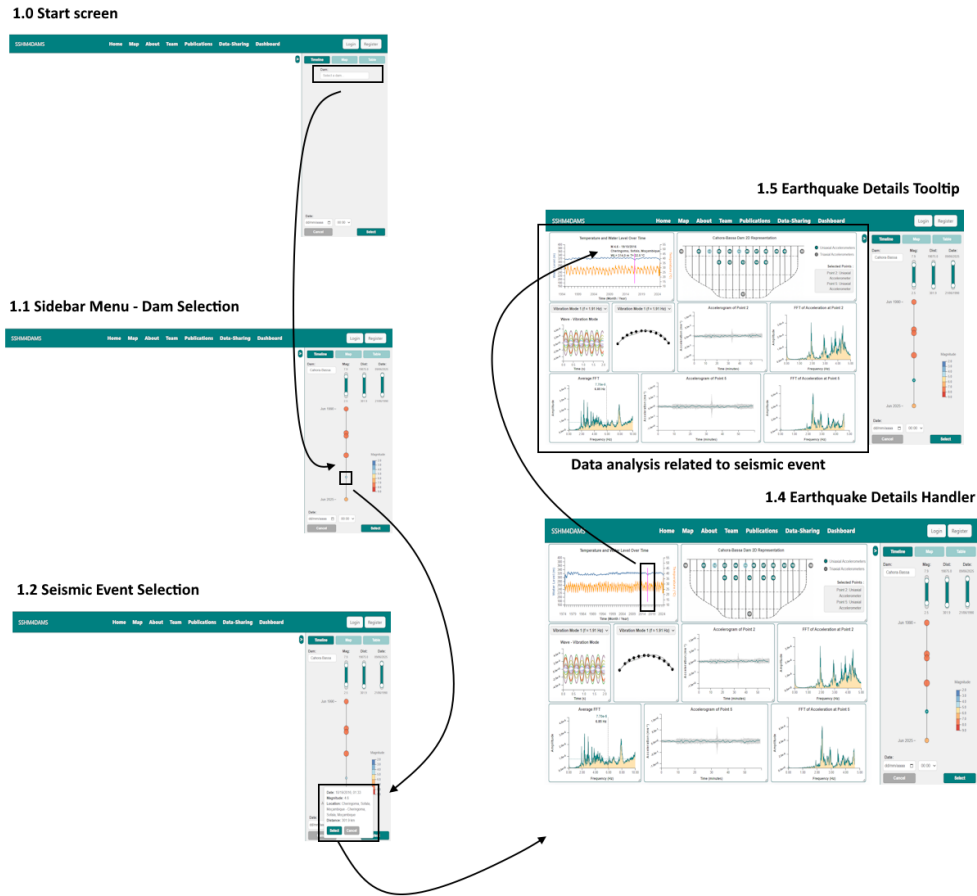


Figure 5.4: UI flow diagram

In summary, the user interface solution for the web application dashboard is designed to be comprehensive, interactive, and user-friendly. These interaction patterns suggest a high level of user engagement with dynamic data elements and highlight the need for intuitive controls and responsive visual feedback.

5.2 Discussion

After completion of all phases of implementation, following the methodology described in Chapter 4 as proposed by Michael Sedlmair, Miriah Meyer, and Tamara Munzner, the final prototype is now fully operational. A comprehensive evaluation of this prototype is presented in the following chapter. It is important to note that this is not yet a production-ready version and will therefore not be made available to the public at this stage. Further database integration refinements, testing, and validation will be necessary before any such release can be considered.

6

Evaluation

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The evaluation of SSHM4Dams involved real-user assessments aimed at evaluating the usability of its user interface, particularly in terms of its suitability and accessibility for tasks related to dam safety control. It is essential to note that the SSHM4Dams dashboard serves as a **proof of concept**. The goal of this evaluation was not only to validate the current implementation but also to gather feedback that would guide future improvements and potential development into a fully deployed operational system.

The testing process was conducted in two distinct phases. The first phase consisted of a pilot test, crucial for verifying and refining the testing methodology, identifying usability issues, and improving both the structure of the tasks and the overall functionality of the dashboard. The second phase involved a full round of user testing with LNEC staff, who were actively engaged in dam monitoring and structural health assessment. Their participation provided valuable insights into how the system performs in realistic operational scenarios.

6.1 Pilot Tests

Before the main user evaluation, a pilot testing phase was conducted to refine the methodology and the test protocol. This phase involved a single participant, Concrete Dam Department (DBB) LNEC specialist, who provided critical feedback on the structure, clarity, and functionality of both the tasks and the SSHM4Dams prototype. We followed the same methodology later used in the main evaluation (see Appendix C). The pilot session allowed for the identification of usability issues and potential improvements in both the prototype interface and task design, as illustrated in the following image 6.1.

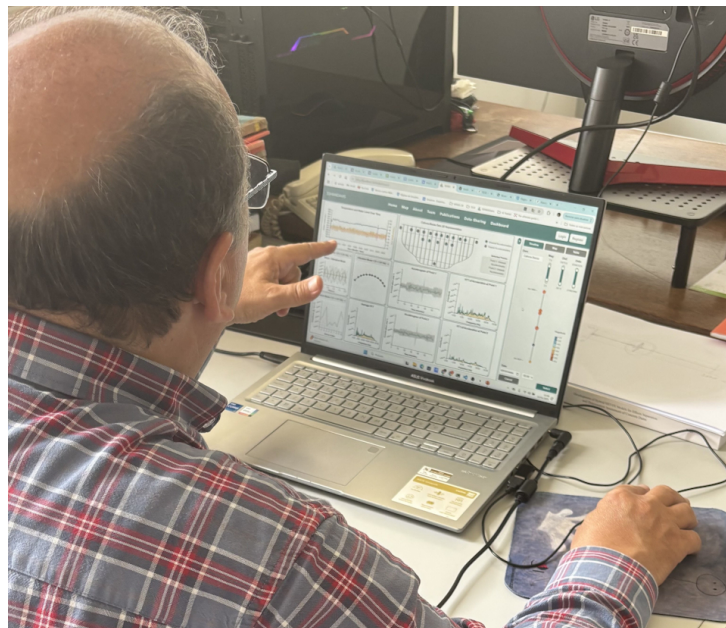


Figure 6.1: Pilot tests

Feedback collected during the pilot testing phase was instrumental in refining the final version of the tests. The following adjustments and improvements were implemented:

- Remove the Sensor Index chart from the dashboard vibration mode view analysis;
- Correct the Accelerogram x-axis, changing the label from “min” to “m”, and updating the axis label to “Time (minutes)” for clarity;
- Update the initial state of the dashboard to hide visualizations until an earthquake or date is explicitly selected;
- Limit the Average FFT x-axis domain to half the original range to improve readability;
- Added new task-related questions to better guide user observations, explicitly prompting them to:
 - Identify temperature and reservoir water level values;

- Determine earthquake magnitude and epicentral distance;
- Classify the earthquake acceleration peak as low, medium, or high;
- Confirm whether a seismic event was detected;
- Recognize observable acceleration patterns across galleries;
- Distinguish between symmetric and antisymmetric vibration modes.

A second pilot test with the updated prototype led to further improvements.

- Improve dam selection interaction by modifying the suggestions input field to default to “A”, enabling immediate display of options;
- Enhance UI contrast by adjusting the background color of unselected tab buttons to a lighter shade;
- Restrict the FFT chart x-axis to a 0–5 Hz range for better data focus;
- Adjust the x-axis label position on the acceleration chart to prevent overlap with the hover line;
- Improve readability in the clickable dam image by changing sensor number colors to white;
- Increase the font size of the timeline’s start and end date labels by 0.1rem to enhance legibility;
- Fix the y-axis scale in the accelerogram plots to remain constant, rather than auto-scaling with the maximum acceleration value.

We conducted a third pilot test, during which no updates were needed to the data entry forms or task protocol. These refinements helped ensure that the final version of the test protocol provided a consistent, intuitive, and effective user experience while maintaining the technical accuracy and relevance required for real-world dam monitoring applications.

6.2 User Evaluation

The primary objective of the evaluation process was to assess the usability of the SSHM4Dams dashboard prototype’s user interface. The evaluation involved real-user testing with LNEC staff directly engaged in various dam analysis and structural health monitoring tasks. This approach provided first-hand feedback on the system’s operation, which was instrumental not only in evaluating its performance, but also in identifying areas for improvement and potential new features.

The tests were conducted in a meeting room in LNEC’s DBB, using computers and other hardware provided by LNEC, as shown in Figure 6.2. Each user participated individually, performing the tasks in a randomized order. A standard A/B testing approach was used, in which participants were divided into

two groups: one group began the evaluation using the SSHM4Dams dashboard and then repeated the assessment in the MATLAB interface, while the other group started with the MATLAB interface before using the SSHM4Dams dashboard. A/B testing [29] is a quantitative research method that tests two or more design variations with a live audience to determine which variation performs best according to a predetermined set of business success metrics.

The author of this work served as both test coordinator and observer, following a test guide (see Appendix C) to ensure consistency and thoroughness throughout the evaluation process.



Figure 6.2: User testing the prototype

Each test session had nine steps as described in Table 6.1:

With the users' consent, several photos were taken during the evaluation sessions. All tasks presented during the evaluation were developed collaboratively with LNEC engineers. These tasks encompassed the use of relevant functionalities of the prototype and were designed to reflect realistic scenarios that typical users may encounter in their day-to-day work. The following tasks were conveyed verbally to participants during each test session.

Tasks 1.1. and 1.2. were designed to evaluate the integration and interaction between key functionalities of the application, particularly the dam and earthquake selection tools located in the sidebar. In

Step	Description
1	Welcome the user and give a brief presentation of the project, including its objectives and how it operates.
2	Provide an overview of the testing process and the prototype.
3	Explain how personal information and data will be used during the session.
4	User completes a consent form for the collection, storage, and use of audiovisual data.
5	User completes an initial questionnaire to gather demographic information.
6	The test coordinator demonstrates the general functionality of the prototype, including navigation through visualizations, selection of dams, earthquakes, or dates in the dashboard, and chart manipulation (pan and zoom).
7	The user performs a free trial of the prototype.
8	The user performs two test tasks in a random order.
9	User completes a final questionnaire to record their experience and opinion regarding the prototype and tasks (Appendix D).

Table 6.1: Steps of the usability testing session

addition, it assessed how users interact with the double-line graph (e.g., by zooming or dragging) and how effectively and quickly they can locate and extract the relevant temperature and water level values from the graph.

Tasks 2.1. and 2.2. aimed to evaluate the user's ability to interpret acceleration data in a comparative context using the dashboard's visualization tools. It tested how users navigated the time series chart to identify patterns indicative of seismic activity and whether they could draw conclusions based on differences or similarities in the data from two distinct monitoring points.

Task 3 is relevant to evaluating the user's interaction with vibration modes, specifically through the modal analysis tools provided in the application. Assesses the user's ability to access and interpret the graphical and numerical representations of the dam's dynamic behavior, particularly the first four vibration modes. This includes identifying symmetric and antisymmetric modes and understanding their physical importance in defining the structural response of the dam.

The set of metrics registered during the tests included both objective and subjective measurements:

6.2.1 User Characterization

The tests were conducted with 10 users, all of whom were members of the LNEC staff. The sample consisted of 60% men and 40% women, with the age distribution shown in Figure 6.3.

The participants had a high level of education: 90% held a university degree — either a Licenciatura (Lic.), Master's Degree (MSc), or Doctoral Degree (PhD) — and the remaining 10% held a High School Diploma (HSD), as illustrated in Figure 6.3. All users were professionally active in the field of dam engineering.

Feature 1: Analyze Earthquake Data

Task 1.1	Select the seismic event that occurred in 2016. Determine the date of the earthquake, its magnitude, and the distance from the epicenter to the dam. Also, identify the reservoir water level (elevation) and air temperature on that day.
Task 1.2	Compare the peak ground acceleration with the maximum acceleration recorded under ambient or operational excitation. Classify the earthquake's intensity at the dam as low, medium, or high.

Feature 2: Investigate Measured Dam Accelerations

Task 2.1	Select December 18, 2023, and the time 09:00 to view measured accelerations between 09:00 and 10:00. Observe the accelerations at points 6 (crest gallery) and 13 (second gallery) using the 2D Dam Representation. Determine if a seismic event is identifiable during this hour.
Task 2.2	Identify which of the galleries exhibits higher amplitude accelerations.

Feature 3: Evaluate Gallery Influence and Vibration Modes

Task 3	Analyze the first four vibration modes. Identify which modes are symmetric and which are antisymmetric. Do not change the previously selected date or earthquake.
--------	---

Table 6.2: User tasks grouped by dashboard features

Although 90% of participants reported having previously used data monitoring systems (e.g., web applications or dashboards), only 50% indicated using them regularly (daily or weekly) in their professional routines.

Additionally, every user had prior experience performing tasks related to the inspection and monitoring of dams, specifically involving parameters such as temperature, accelerations, and water levels.

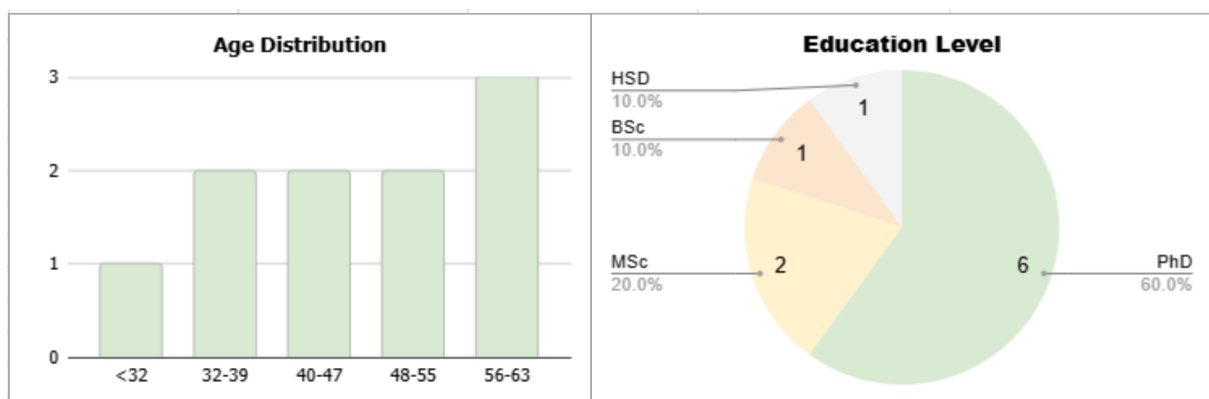


Figure 6.3: Age distribution and education level of the participants

Measurement Type	Metrics
Objective Measurements	• Time required to complete tasks (in seconds) • Number of mistakes or incorrect clicks during task completion
Subjective Measurements	• Overall ease of use • Visual appeal and UI intuitiveness • Readability of the charts • Effectiveness for visual assessments

Table 6.3: Objective and subjective usability metrics

6.2.2 Evaluation Results

Regarding the objective metrics recorded during the test, all users completed the tasks successfully, with completion times of less than 360 seconds for the SSHM4Dams dashboard and less than 524 seconds for the MATLAB system (6.4).

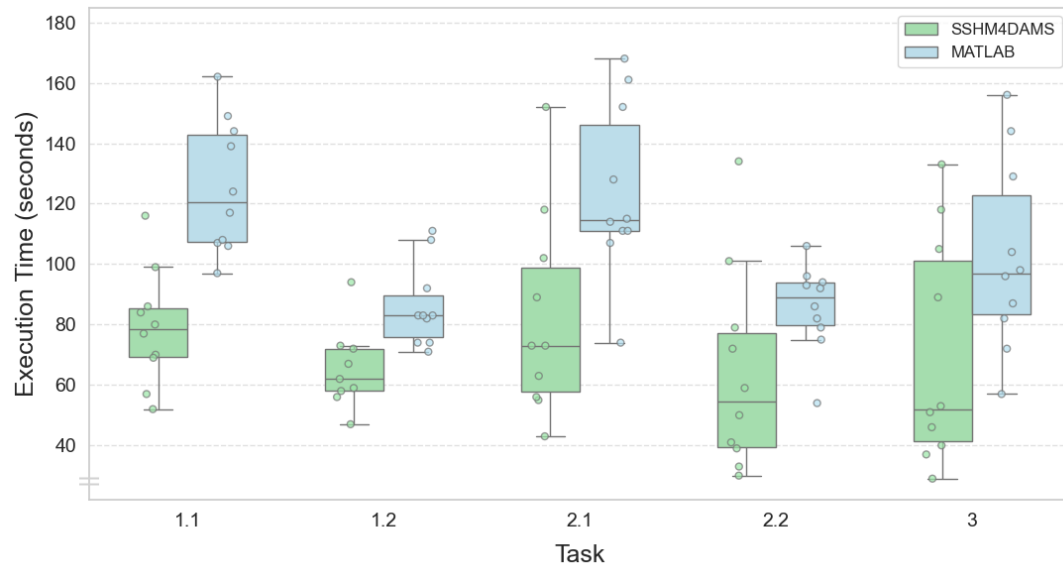


Figure 6.4: Objective metrics - execution time comparison across tasks and platforms

On the other hand, the number of wrong or failed operations in the SSHM4Dams dashboard was very low across all tasks. Specifically, 60% of users completed task 1.1 with no errors, 80% completed task 1.2 with no errors, 50% completed task 2.1 with no errors, 70% completed task 2.2 with no errors, and 80% completed task 3 without errors (Figure 6.5). Furthermore, the maximum number of errors

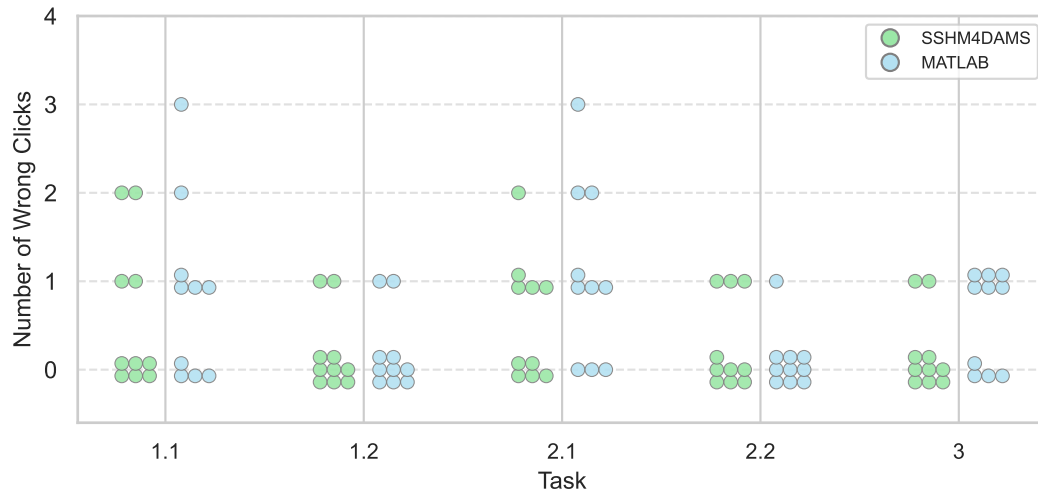


Figure 6.5: Objective metrics - number of wrong clicks across task and platforms

made by a single user was 5. Similarly, in the MATLAB system, the number of wrong clicks was also low: 40% of users completed task 1.1 with no errors, 80% completed task 1.2 with no errors, only 30% completed task 2.1 with no errors, 90% completed task 2.2 with no errors, and 40% completed task 3 with no errors. The maximum number of wrong clicks made by a single user in this system was 7.

In the domain of subjective metrics, these were collected through a questionnaire in which users rated the different aspects of their experience. The questions used a Likert scale ranging from 1 (the least favorable) to 7 (the most favorable) (6.4). Regarding the general operation of the prototype, the vast majority of users considered the prototype to have a friendly and intuitive UI (70% rated 7 and 30% rated 6), but had a less favorable opinion about the ease of use (60% rated 7 and 40% rated 6 or 5). In contrast, the MATLAB system received slightly lower ratings in terms of user interface intuitiveness and ease of use. While still positively evaluated, the median for overall ease of use was 5 with an IQR of 2, indicating a more varied perception among users. UI intuitiveness scored a median of 6 (IQR 1), suggesting that users found it reasonably intuitive, but slightly less so than the SSHM4Dams dashboard.

The usability in real-world scenarios, reflecting how useful each system would be in users' daily professional tasks, was rated with a median of 6 (IQR 1) for SSHM4Dams. Among participants, 40% rated this aspect as 7, another 40% gave it a 6, and the remaining 20% rated it a 5. These results suggest a generally positive reception. In comparison, the MATLAB system was rated slightly lower in this regard, with a median of 5 (IQR 1), suggesting users recognized its potential but viewed it as slightly less suitable for seamless integration into routine workflows.

In terms of effectiveness for visual assessments, the prototype was also favorably rated. A total of 60% of users gave the maximum score of 7, while the remaining 40% provided ratings of 5 or 6. This suggests that most users found the visual components of the dashboard to be effective for analyzing

data. MATLAB also performed well in this area, though with slightly more spread responses (median 6, IQR 2), indicating variability in user perceptions regarding its capability to visually present data.

In addition, for the straightforward of the interaction, user feedback was consistent with previous metrics. Here, 40% of the participants rated the system 7, another 40% rated it 6, and 20% rated it 5 or lower (median 6, IQR 1). This indicates that while most users found the interface intuitive and easy to navigate, a small portion encountered minor difficulties or required additional time to become familiar with certain functionalities. MATLAB showed similar variation, with a median of 5 and IQR of 1 (20% rated 6, 60% rated 5, and 20% rated 4 or lower), indicating that users may have found it slightly less direct or requiring more steps to achieve goals. Concerning the visual appeal category, 60% of the users rated it 7, while 40% rated it 6 or 5. In contrast, for MATLAB, 30% of the users rated it 6, 50% rated it 5, and 20% rated it 4. These findings are crucial in determining user satisfaction with the interface and overall experience, as well as their desire for frequent system involvement.

Table 6.4: Answers to questionnaires (median and inter-quartile range), regarding each criterion

Category	SSHM4DAMS		MATLAB	
	Median	IQR	Median	IQR
Prototype				
Overall ease of use	7	1	5	2
Effectiveness for visual assessments	7	1	6	2
Usability in real-world scenarios	6	1	5	1
UI intuitiveness	7	1	6	1
Straightforward	6	1	5	1
Visual Appeal	7	1	6	1
Tasks				
Easiness of tasks	7	0	6	1
Selections				
Easiness of dam selection	7	0	4	2
Easiness of seismic event selection	7	0	5	2
Easiness of date selection	7	0	6	1
Ease in accelerometers/sensors selection	7	1	7	1
Charts				
Water-level and Temperature Chart Readability and Easiness	7	1	7	1
Accelerograms Readability and Easiness	7	1	6	1
Vibration Modes Readability and Easiness	7	0	7	0

Regarding the execution of the five tasks during the test session, users generally considered all tasks to be easy to complete, with 80% rating them a 7 and 20% rating them a 6. When evaluating task execution of SSHM4Dams dashboard, most users found all five tasks easy to complete: 80% rated them a 7 and 20% rated them a 6. In MATLAB system, this criterion had a median rating of 6 (IQR 1), suggesting that users generally found tasks feasible but slightly more demanding than in SSHM4Dams (30% of users rated 7, 50% rated 6, and 20% rated 5 or lower).

Users reported that the dashboard facilitated easy selection of specific parameters. The selection of a dam was rated as very straightforward by most users (90% rated 7, 10% rated 6). Selecting a

seismic event was also considered easy (80% rated 7, while 20% gave a 6 or lower). Choosing a date was regarded as the most intuitive feature, with all users rating it a 7. The selection of accelerometer points, represented as clickable markers, received slightly more varied feedback (60% rated 7, and 40% rated 6 or lower), suggesting that some users may have required brief familiarization with the interface. The MATLAB dashboard, on the other hand, showed greater variability. Dam selection received the lowest ratings, with a median of 4 (IQR 2). Seismic event selection received a median of 5 (IQR 2). Date selection was more favorably perceived, with a median of 6 (IQR 1). For the selection of sensors, MATLAB received high scores (median 7, IQR 1); specifically, 50% of users rated it a 7 and 50% rated it a 6. This indicates that users generally found this functionality well-designed and accessible in both systems.

With regard to the charts, which present the evolution of recorded data over time, users generally found them effective for identifying desired values and responses. Regarding the SSHM4Dams dashboard, the water level and temperature chart was rated a 7 by 60% of users, while 40% rated it a 6 or lower. For accelerograms, 50% of users rated them a 7 and the remaining 50% rated them a 6 or lower. The vibration mode representations were especially well-received, with 80% of users giving the highest rating of 7 and the remaining 20% rating them a 6. In the MATLAB system, the water level and temperature chart was rated a 7 by 70% of users and a 6 or lower by 30%, suggesting slightly better readability and a more intuitive interaction than in the SSHM4Dams dashboard. The readability and ease of use of the accelerogram charts were rated a 7 by 40% of users, a 6 by another 40%, and a 5 by the remaining 20%. Finally, the vibration mode charts received high marks as well, with 80% of users rating them a 7 and 20% rating them a 6. Overall, while both systems were positively received, the SSHM4Dams dashboard generally achieved higher and more consistent user satisfaction across all subjective dimensions, particularly in usability, simplicity, intuitiveness, and ease of task execution.

6.3 Discussion

User evaluation was primarily conducted to compare the traditional MATLAB system with the modern, web-based SSHM4Dams dashboard. Overall, participants expressed high satisfaction with the functionality and UI of both systems. However, they found the SSHM4Dams dashboard to be easier to use, more intuitive, and overall more useful. Many participants also expressed enthusiasm about its potential to improve their workflows and eventually replace the MATLAB-based dashboard.

The five evaluation tasks were completed quickly, and users made minimal errors, a result that was unexpected given the limited time they had to explore the interface. Users found it easier and more intuitive to complete the tasks in our solution. While tasks 1.2, 2.2, and 3 involved only a few steps, tasks 1.1 and 2.1 required users to engage with a broader range of features, including the selection of

dams, seismic events, sensors, and dates, as well as interaction with multiple visualization methods.

The SS4Dams dashboard execution times were consistently shorter across all tasks, mainly because data processing and loading are automated. In contrast, the MATLAB dashboard required users to manually insert the file corresponding to the specific day and hour for which they wanted to view data. We conclude that our dashboard is more efficient and effective based on the observed execution times. However, for a more comprehensive evaluation, it is ideal to test with a larger number of tasks and incorporate additional functionalities offered by our solution to ensure and further validate its overall superiority.

One of the main objectives of a dashboard is to present easy-to-understand and readable data through charts, and this goal can be considered successfully achieved in both systems based on user feedback. However, some users reported that the web application was slow, a limitation attributed to the use of locally stored acceleration data instead of leveraging the more efficient MongoDB database. Transitioning the acceleration datasets to MongoDB is expected to improve performance and reduce query response times significantly. All other data, such as seismic events, dams, and related data, are already stored in MongoDB. Additionally, several users noted that due to the complexity and variety of visualizations, a longer familiarization period may be necessary to adapt to the dashboard fully.

Beyond the structured questionnaire feedback, users also provided informal written and verbal comments about specific aspects of the prototype. Many were proactive in offering suggestions for improvement, such as unifying the vibration mode selection across the wave chart and vibration mode representation, and optimizing overall efficiency through database improvements.

7

Conclusion

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This work explored the use of a monitoring dashboard in the context of the structural monitoring of large Civil Engineering structures, such as dams. In particular, the study aimed to investigate whether data visualizations could be effectively used in the context of dam safety control, specifically by providing visualization capabilities that are not available through traditional methods.

Using the tool, inspectors can access detailed information on the evolution of accelerations, frequencies, and displacements recorded by selected sensors over time. These structural data are presented alongside the evolution of key environmental variables, such as temperature and water level, providing insight into the dam's behavior under various operational and environmental conditions. By allowing the visualization of complex information on a single-page web application, the dashboard offers a more intuitive and efficient approach to data exploration and interpretation.

The research was supported by the development and evaluation of SSHM4Dams – Dam Monitoring Dashboard, a web application designed to assist inspectors during their regular dam inspection activities. The traditional MATLAB solution is useful to provide a conclusive comparative analysis between new and

old visualization techniques and methods. The dashboard is tailored for preventive monitoring and post-seismic event evaluations, providing actionable insights into the structural behavior and health status of the dam in response to such events. In general, it enables dam operators to immediately detect when the structural integrity of the dam is compromised and respond accordingly to protect downstream communities, infrastructure, and environmental resources.

7.1 Achievements

The greatest achievement of this work was to demonstrate that, by applying the methodology proposed in [26], it is possible to efficiently use interactive data visualizations for dam safety control. In addition, we successfully developed a solution that supports and accelerates decision-making in dam operations compared to traditional methods. This constituted the main objective of the investigation and was achieved despite less than ideal conditions, particularly the unavailability of several datasets for use in the case study, as discussed in Section 5.1.1. Furthermore, the prototype evaluation and the conclusion-drawing phase are notable achievements that positively contribute to establishing and highlighting the usability and necessity of this prototype.

Another important achievement was the successful development of a fully functional prototype, based on real-world data, that can effectively be used in a professional monitoring context. The prototype features a simple and intuitive user interface, making it accessible even to users with limited technical experience. It allows for quick navigation through the different sidebar tabs and provides the information necessary to understand the structural response of the dam to environmental changes.

The SSHM4Dams dashboard met the general requirements and expectations of the client institution (LNEC), particularly in allowing visualization of vibration modes and the corresponding amplitude values between different sensors. An additional key feature is the seismic event selector, accessible through sidebar tabs and enhanced by visual encoding techniques, such as color, size, and position, that improve usability and interpretation. The strategies adopted in collaboration with master thesis advisors to overcome challenges can also be considered an important achievement. These approaches reflect a creative use of existing technologies, enhancing the overall performance and flexibility of the system.

Finally, the decision to implement the system as a single-page web application significantly improved both accessibility and user experience. These prevent disjointed navigation and ensure the seamless integration of multiple data visualizations, which is essential to preserve the context and consistency needed for accurate dam behavior analysis. Fragmented interfaces could otherwise compromise the interpretation of such critical data.

7.2 Constraints and Future Work

Despite the positive outcomes achieved with the development and deployment of the SSHM4Dams dashboard, several limitations were identified throughout the process, which also point to clear directions for future work. Currently, the system relies on data from a single dam, which limits the scalability of dashboard functionality. For the tool to be adopted in broader dam safety monitoring efforts, the underlying database must be updated and expanded to include data from all relevant dam structures. This would enhance the system's capacity to deliver comparative analysis and increase its practical value for international or national monitoring programs.

The current implementation uses the standard Fast Fourier Transform (FFT) method for frequency analysis. Although effective, this approach may not always provide the most accurate or stable estimates, particularly in the presence of noisy signals. As a next step, the integration of more robust spectral analysis techniques, such as the Welch method, is proposed. This would enhance the reliability of frequency content estimations and provide smoother spectra, which is especially beneficial for identifying vibration modes.

An important area for future development is the implementation of an alarm system that can automatically notify users when critical thresholds are exceeded. This system could be based on AI-driven anomaly detection models trained on historical data or rule-based thresholds defined by engineers. This functionality would greatly improve the role of the dashboard in preventive monitoring and early warning, improving safety, and enabling faster response in critical situations.

It is essential to evolve this proof-of-concept into a fully functional version that incorporates all the limitations and constraints outlined in this chapter. This step is indispensable to ensure the robustness, reliability, and readiness of the dashboard for deployment in the SSHM4Dams website.

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A

Dashboard Sketches

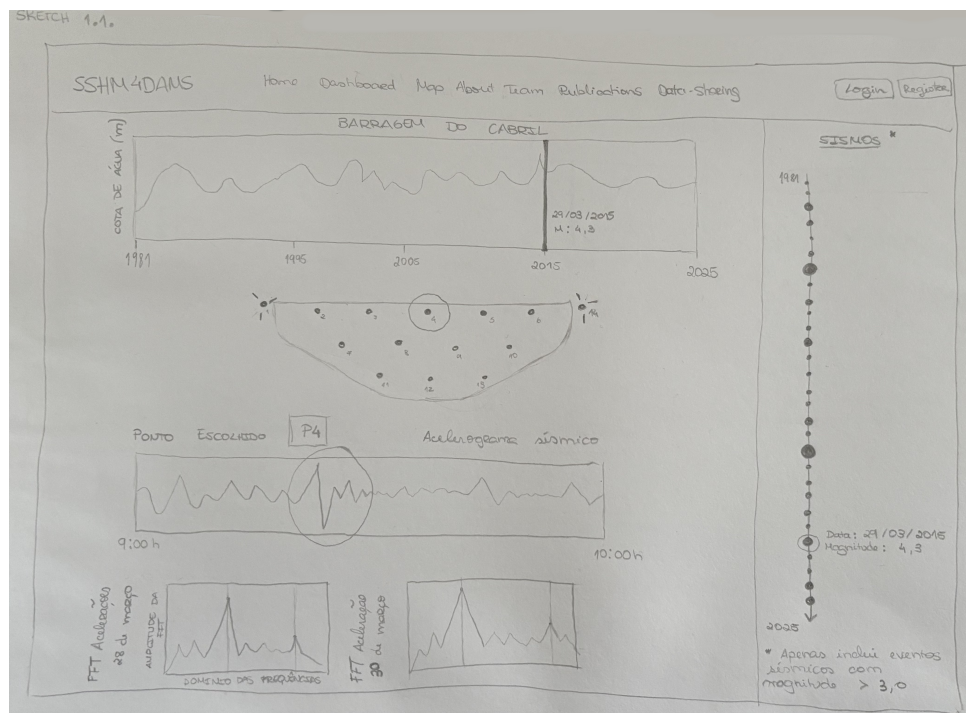


Figure A.1: First Dashboard Sketch - Time-Centric Overview

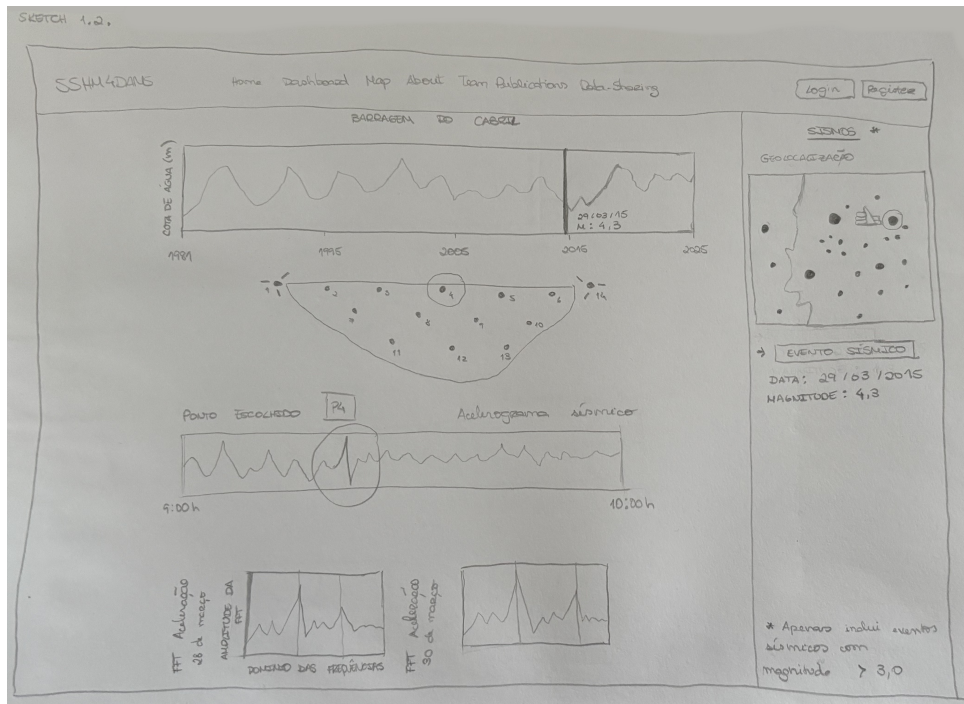


Figure A.2: Second Dashboard Sketch - Location-Based Monitoring

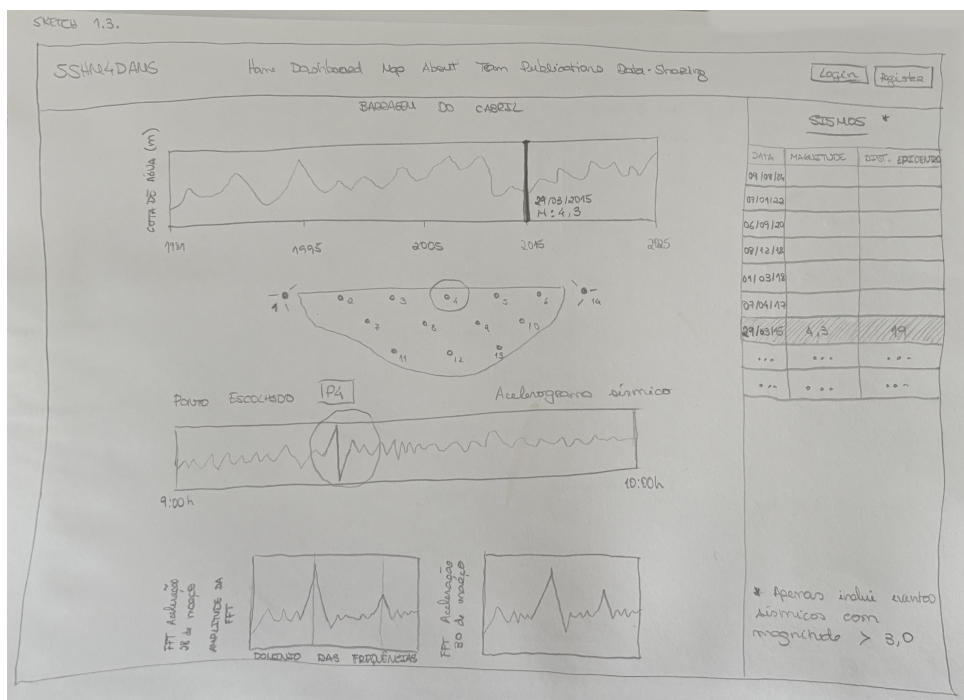


Figure A.3: Third Dashboard Sketch - Hybrid Approach

B

Seismic Events and Dam Stability

Storyboard

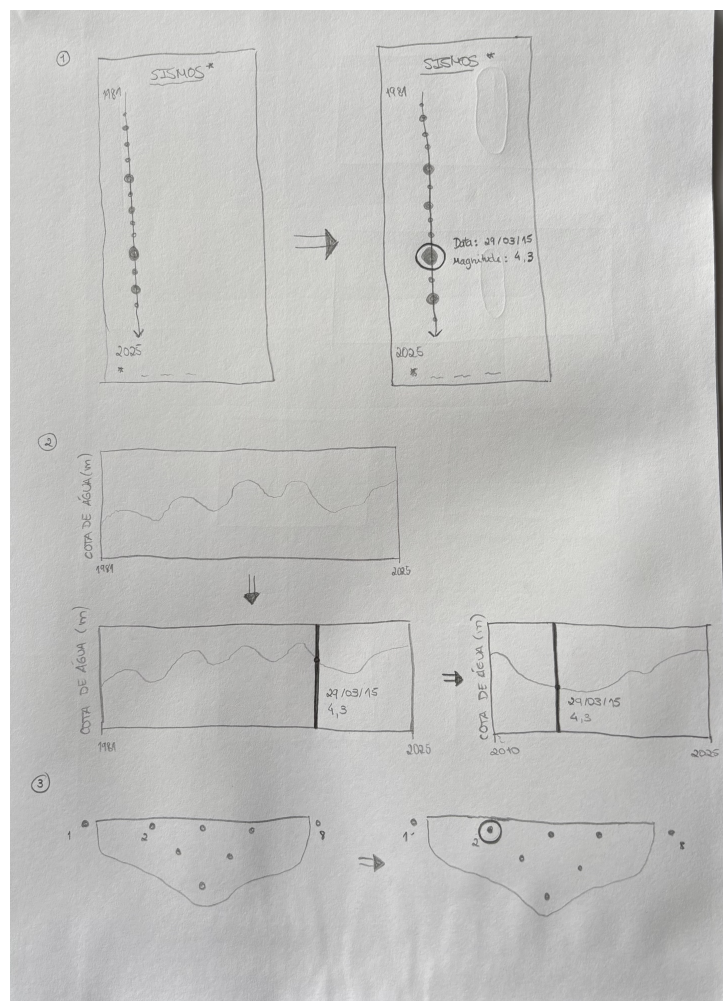


Figure B.1: Changes based on user interactions with dashboard features

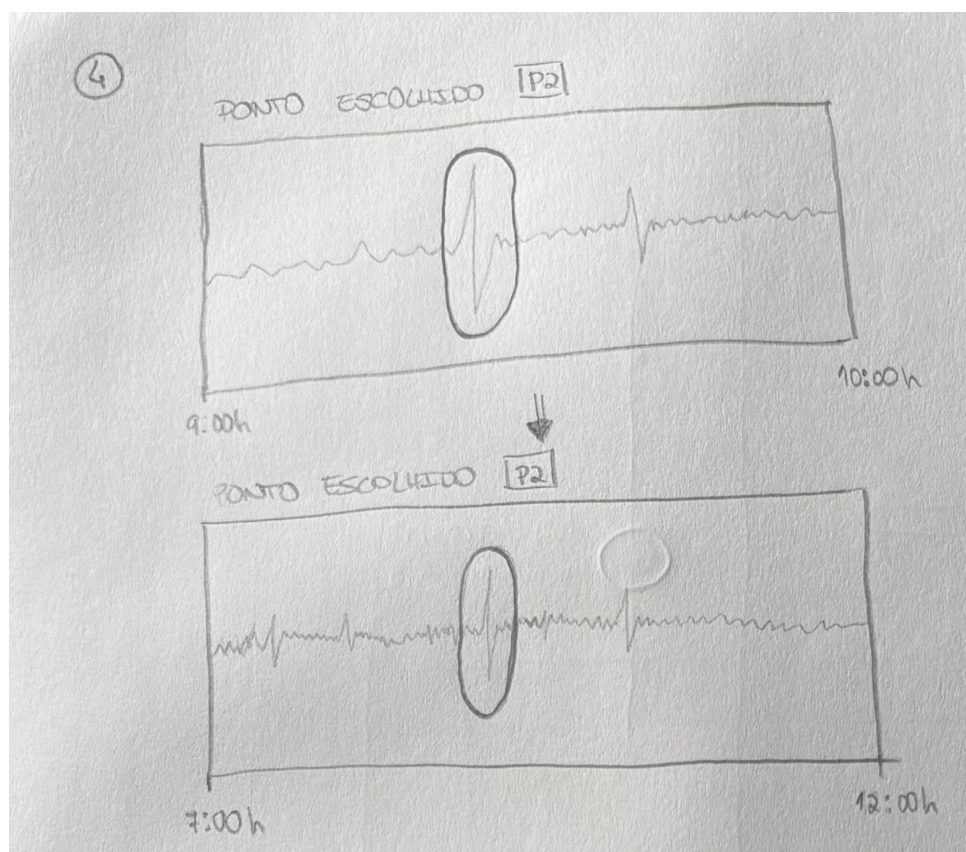


Figure B.2: Adjusting the time interval for analysis by zooming in and out

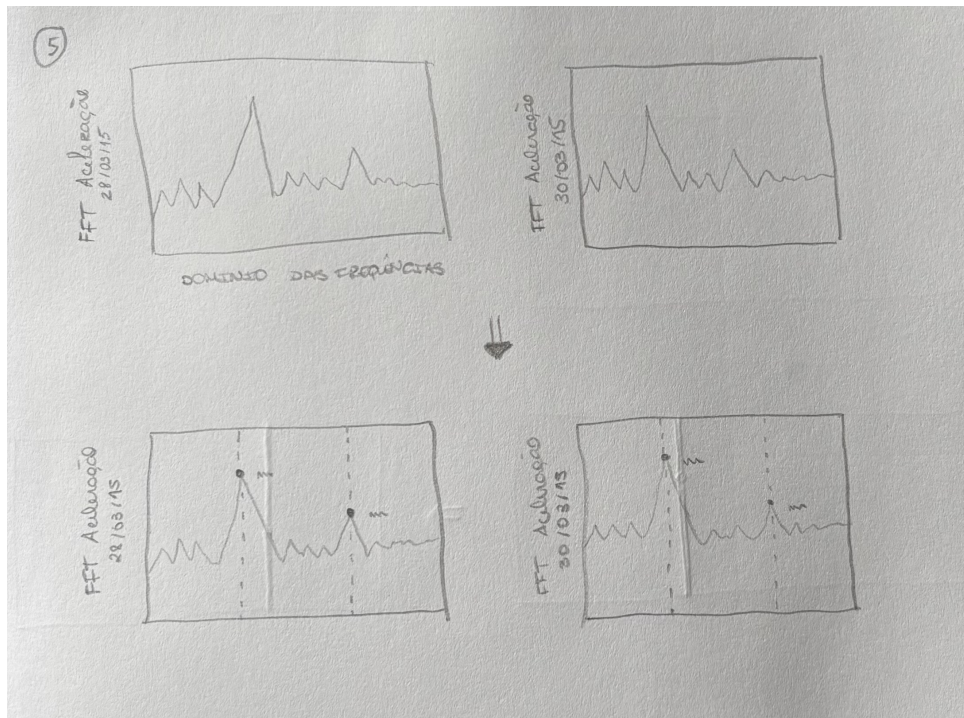


Figure B.3: Events appearing in the storyboard after selecting a monitoring point in the 2D dam visualization



Test Guidelines

This appendix includes the test guide, used by the observer/coordinator during the prototype user evaluation.

- **Materials:**

- Keyboard and mouse
- Monitor

- **Hardware:**

- * **PC Specification:**

- CPU: 11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz
 - RAM: 16GB

- **Software:**

- * Node.js

- **Setup:**

- Reset the workspace and sanitize all equipment.
- Launch MATLAB and the SSHM4Dams application on the computer.

- Use OBS to record the session.
- Document observations and take photographs, if the participant consents to being recorded.
- Video Link: <https://app.heygen.com/share/a11bfcabd46c4e569345d492ff50c8bd>

User Test Session - Methodology

• Introduction - Greeting

- Welcoming the participant to the usability testing session. ("Bom dia! Seja muito bem-vindo à fase de testes de utilizadores do projeto SSHM4Dams.")

• Session Overview

- Providing a brief overview of the testing process and the prototype. ("Durante esta sessão, irá testar duas aplicações equivalentes em modo desktop que proporcionarão o acesso a um sistema de monitorização de dados de barragens, por outras palavras um dashboard. Uma delas será uma versão em Matlab e a outra, acessível através de um website. O grande intuito destas aplicações é facilitar e colaborar nos processos de tomada de decisão dos operadores de barragens, garantindo assim que estas estruturas estão em boas condições de manutenção e que não apresentam riscos para as comunidades e ecossistemas que ali coexistem.")

• Prototype Explanation

- Explaining the nature of the prototype being tested. ("É importante mencionar que irá testar um protótipo final, o que significa que não é um produto final e pode apresentar comportamentos indesejados, pois está sujeito a modificações e correções.")

• Reassurance on Task Difficulty

- Reassuring the participant that any difficulties encountered are helpful for improvement. ("Se encontrar dificuldades em completar alguma tarefa, isso indica que o protótipo pode necessitar de alguma melhoria. Portanto, qualquer dificuldade que sinta durante o período de realização do teste, será útil para o nosso trabalho, por isso agradecemos que nos reporte essas situações.")

• Privacy and Data Usage

- Outlining how personal information and data will be used during the session. ("Será solicitado que preencha um formulário de consentimento para autorizar ser fotografado e filmado durante o teste. As fotos, áudios e vídeos serão usados exclusivamente para fins de pesquisa científica.")

• Forms Completion

- Asking the participant to complete the necessary forms before starting the test. (“Por favor, preencha o formulário de Consentimento Informado. De seguida, preencha o formulário de Caracterização do Usuário.”)

(A/B Testing) - A group of users will begin by performing tasks in MATLAB, while another group will start by testing our dashboard.

All tasks presented here were developed in collaboration with LNEC engineers.

- **Demonstration and Training (SSHM4DAMS Dashboard Prototype)**

- Briefly explain the main steps of the session. (“Primeiro vou explicar o modo de funcionamento do protótipo e de seguida vai-lhe ser fornecido um período para habituação à aplicação. Depois irá ter de realizar 2 tarefas.”)
- Demonstrates how the prototype operates (1/2 min - video link on top of user testing protocol) - (“Para seleccionar uma barragem clica-se no dam input da sidebar.”; / “Para escolher um sismo pode-se seleccionar qualquer uma das tabs porque estão conectadas.”; / “Explicar onde se pode seleccionar um dia e hora específico”; / “Explicar como se faz através do rato, o mouseOver nos gráficos e o display de labels com os valores dos dados representados no eixo x/y.”; / “Seleccionar e deseleccionar um ponto na representação 2D da barragem.”; / “Mostrar onde se pode alterar os modos de vibração”.)
- Ask the participant to perform the Habituation Task (2 mins each): “Selecione a barragem “Cahora-Bassa” e interaja com a interface.”; “Exprimente o mouseOver no gráfico da Temperatura e da Cota de Água”; Selecione um sismo; Selecione uma data; Selecione e a desselecione pontos da representação 2D da barragem; Altere o modo de vibração num dos gráficos (Wave Chart, Vibration Mode Chart. . .).
- During the entire session: Take any screenshots or screen records; Take any photo or record a video of the participant in action; Take notes of participant behavior, body, and facial expressions; Take notes on how well they are accomplishing the tasks.

The following tasks were conveyed verbally to participants during each test session.

- **Tasks - (SETUP: All tasks involve data from the Cahora-Bassa dam.)**

- Feature 1: Analyze Earthquake Data
 - * Task 1.1. Select the seismic event that occurred in 2016. On what day did the earthquake occur, and what were its magnitude and the distance from the epicenter to the dam? What were the reservoir water level (elevation) and the air temperature on that day? / Selecione o evento sísmico ocorrido em 2016. Em que dia ocorreu o sismo e qual a magnitude e a

distância do epicentro à barragem? Qual a cota de água da albufeira e a temperatura do ar nesse dia?

- * Task 1.2. When comparing the peak ground acceleration values with the maximum acceleration values recorded under ambient/operational excitation, how would you classify the intensity of the earthquake measured at the dam: low, medium, or high? / Comparando os valores da aceleração sísmica de pico com os valores de aceleração máximos registados sob excitação ambiente/operacional, como classificaria a intensidade do sismo medido na barragem: pequena, média ou alta?

– Feature 2: Investigate Measured Dam Accelerations

- * Task 2.1. Select December 18, 2023, and the time 09:00 to view the measured accelerations between 09:00 and 10:00. Observe the accelerations at points 6 and 13 (located in the crest gallery and the second gallery, respectively). Note: Select the points on the 2D Dam Representation. Is it possible to identify a seismic event during this hour? / Selecione o dia 18/12/2023 e a hora 09h para visualizar as acelerações medidas entre a 09h e as 10h. Observe as acelerações nos pontos 6 e 13 (galeria do coroamento e 2.^a galeria. Nota: selecione os pontos na Representação da Barragem em 2D. É possível identificar um evento sísmico nesta hora?
- * Task 2.2. Which of the galleries shows higher amplitude accelerations? / Qual das galerias apresenta acelerações com maior amplitude?

– Feature 3: Evaluate Gallery Influence and Vibration Modes (Do not change the previously selected date or earthquake.)

- * Task 3. Analyze the first four vibration modes. Identify which modes are symmetric and which are antisymmetric. / Analise os quatros primeiros modos de vibração. Identifique os simétricos e os antissimétricos.

The initial state of the system, with which the user will begin the tasks, will be as follows: the applications will already be running, and time for data processing and database retrieval will be accounted for comparative performance purposes.

• **Post-test Survey - Routine**

- After all prototype task tests, ask the participant to complete the Feedback Forms. (“Agora irá preencher um questionário para feedback da aplicação.”)
- After the test is concluded, thank the participant for their time. (“Obrigado pela sua disponibilidade na realização dos testes.”)
- Keep a copy of the acquired data (photos, video, audio).

- Keep a copy of the application data.
- Clean up the working space.

- **Objective Measurements:**

- Time required to complete each task;
- Number of mistakes during the completion of tasks;
- User Interface button presses / Key presses.

- **Subjective Measurements:**

- User interface intuitiveness;
- Visual Friendliness;
- Readability of charts;
- Global ease of use;
- Effectiveness for visual assessments.



Test Questionnaire - Final Feedback Forms

This appendix includes the final questionnaire that was filled out by the participants of the tests.

Formulário de Feedback

[Inicie sessão no Google](#) para guardar o seu progresso. [Saiba mais](#)

Questões gerais relativas ao protótipo acedido no website SSHM4DAMS:

Assinale com um X o seu grau de concordância (entre 1 - total discordância e 7 - plena concordância) com as afirmações seguintes:

(marque apenas uma opção em cada linha)

SSHM4DAMS Dashboard



Acho que gostaria de utilizar este sistema com frequência.

1 2 3 4 5 6 7

Discordo Totalmente

☐ ☐ ☐ ☐ ☐ ☐ ☐

Concordo Totalmente



Considere o sistema mais complexo do que necessário.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Achei o sistema fácil de utilizar.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Acho que necessitaria de ajuda de um técnico para conseguir utilizar este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Considere que as várias funcionalidades deste sistema estavam bem integradas.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Achei que este sistema tinha muitas inconsistências.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



Suponho que a maioria das pessoas aprenderia a utilizar rapidamente este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Considereei o sistema muito complicado de utilizar.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Senti-me muito confiante a utilizar este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Tive que aprender muito antes de conseguir lidar com este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

[Anterior](#)[Seguinte](#)[Limpar formulário](#)

Nunca envie palavras-passe através dos Google Forms.

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Questões gerais relativas ao protótipo acedido no MATLAB:

Assinale com um X o seu grau de concordância (entre 1 - total discordância e 7 - plena concordância) com as afirmações seguintes:

(marque apenas uma opção em cada linha)

Acho que gostaria de utilizar este sistema com frequência.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Considerarei o sistema mais complexo do que necessário.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Achei o sistema fácil de utilizar.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



Acho que necessitaria de ajuda de um técnico para conseguir utilizar este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Considerei que as várias funcionalidades deste sistema estavam bem integradas.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Achei que este sistema tinha muitas inconsistências.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Suponho que a maioria das pessoas aprenderia a utilizar rapidamente este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Considerei o sistema muito complicado de utilizar.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



Senti-me muito confiante a utilizar este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Tive que aprender muito antes de conseguir lidar com este sistema.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

[Anterior](#)[Seguinte](#)[Limpar formulário](#)

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Formulário de Feedback

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As seguintes questões são todas relativas à aplicação SSHM4Dams.

Assinale com um X o seu grau de concordância (entre 1 - total discordância e 7 - plena concordância) com as afirmações seguintes:

(marque apenas uma opção em cada linha)

Foi fácil realizar as tarefas.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

A representação do dashboard é intuitiva / acessível.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil seleccionar uma barragem.

1 2 3 4 5 6 7
Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



É fácil selecionar um sismo.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil selecionar uma data.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil analisar os dados do gráfico do nível de água e temperatura.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil selecionar os pontos da representação gráfica em 2D da barragem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É difícil analisar os acelerogramas e as correspondentes FFT.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



É difícil analisar os modos de vibração da barragem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil identificar semelhanças nos acelerogramas de pontos opostos na barragem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

[Anterior](#)[Seguinte](#)[Limpar formulário](#)

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Formulário de Feedback

As seguintes questões são todas relativas ao dashboard em MATLAB.

Assinale com um X o seu grau de concordância (entre 1 - total discordância e 7 - plena concordância) com as afirmações seguintes:

(marque apenas uma opção em cada linha)

Foi fácil realizar as tarefas.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

A representação do dashboard é intuitiva / acessível.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil seleccionar uma barragem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



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1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil selecionar uma data.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil analisar os dados do gráfico do nível de água e temperatura.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É fácil selecionar os pontos da representação gráfica em 2D da barragem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

É difícil analisar os acelerogramas e as correspondentes FFT.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente



Formulário de Feedback

[Inicie sessão no Google](#) para guardar o seu progresso. [Saiba mais](#)

As seguintes questões são todas relativas à aplicação SSHM4Dams.

Assinale com um X o seu grau de concordância (entre 1 - total discordância e 7 - plena concordância) com as afirmações seguintes:

(marque apenas uma opção em cada linha)

O protótipo *SSHM4Dams Dashboard* é um bom complemento para as ferramentas que utilizo na minha atividade laboral.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Esta aplicação pode ser útil para a garantia das condições destas infraestruturas estudadas como também para a segurança das populações e dos ecossistemas que ali coexistem.

1 2 3 4 5 6 7

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

Quais foram os aspetos que considera serem mais positivos do protótipo?

A sua resposta



Quais foram os aspetos que considera serem mais negativos do protótipo?

A sua resposta

Outros comentários:

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