ORIGINAL ARTICLE

Developing a Real-Time Behavioural Safety Culture Framework (BOSCA) Using Progressive Web Applications (PWA)

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ABSTRACT

Introduction: The oil and gas industry's complex operations demand a proactive safety culture that addresses behavioural safety challenges. Traditional safety management systems often fall short in promptly identifying safety culture performance, risk and enabling timely interventions. This study introduces the Behavioural Occupational Safety Culture Application (BOSCA), a framework that leverages Progressive Web Application (PWA) technology to enhance safety culture through integrated behavioural elements. **Methods:** BOSCA was developed through a structured four-phase process: requirements gathering, design, implementation and testing. Key safety elements were identified through expert consultations with stakeholders, including safety practitioners, authorities, academicians, and management. These consultations prioritized eight behavioural sub-elements: management commitment, safety commitment, safety ownership, safety training, safety communication, reward recognition, safety investment and safety competency, which were then integrated into BOSCA's multi-layered architecture. The application was designed for cross-platform functionality to ensure accessibility and usability. **Results:** The BOSCA framework successfully supports continuous monitoring of safety-related behaviours and provides timely feedback to management, enabling proactive interventions. The system integrates an intuitive interface that promotes active user engagement and seamless data processing to reinforce safe behaviours. Internal system testing confirmed that all feedback modules functioned as intended. **Conclusion:** BOSCA represents a significant advancement in safety management for high-risk industries. While potential challenges such as integration with legacy systems and data privacy need addressing, BOSCA's framework sets a new standard for safety culture, fostering a safer, more engaged workforce within the oil and gas sector.
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INTRODUCTION

Safety culture is increasingly recognised as a fundamental component of risk management in the oil and gas industry (1–4). Despite various safety initiatives, the industry continues to report high rates of accidents and incidents (5–7). The complex and high-risk nature of operations in this sector necessitates a safety culture that not only shapes behaviours but also serves as a proactive measure against potential risks. Traditional safety management systems, which rely heavily on retrospective data analysis and manual documentation, have long served as the backbone of risk management. However, these conventional approaches often fall short in promptly identifying hazards and communicating risks, particularly in dynamic environments where timely responses are critical (8–10). Their reactive nature, with a primary focus on compliance, limits their ability to foster a proactive and prevention-oriented safety culture. This reliance on lagging indicators and post-incident evaluations can delay corrective actions, leaving organisations exposed to unforeseen safety threats (11, 12).

As the oil and gas industry faces increasingly complex operational challenges, there is a pressing need for innovative solutions that bridge the gap between reactive systems and proactive safety management. Such approaches must support real-time decision-making and enhance organisational adaptability in mitigating risks (13–15). Recent technological advancements offer promising opportunities to transform safety management. Tools such as real-time data collection, automated analytics, and digital feedback mechanisms enable more immediate and data-driven safety interventions (16, 17). Nevertheless, existing safety frameworks often fail to integrate these technologies into a cohesive structure that systematically addresses behavioural and cultural dimensions of safety (18, 19).

This critical gap underscores the need for a comprehensive digital framework tailored to the unique operational context of the oil and gas industry.

To address this gap, the following research question was formulated:
How can a Progressive Web Application (PWA) be systematically developed to incorporate behavioural safety culture elements for improving proactive safety management in the oil and gas industry?

This study introduces the development of the Behavioural Occupational Safety Culture Application (BOSCA), a digital framework designed to address the limitations of conventional safety systems. BOSCA leverages state-of-the-art technologies to enable continuous monitoring and analysis of safety behaviours, facilitating real-time feedback and timely interventions (20–22). By providing instant insights to management, the system helps mitigate safety risks before they escalate (23, 24).

The primary aim of this study is to develop a comprehensive and user-centric safety management application that integrates critical behavioural elements into a scalable PWA. Through intuitive interfaces, interactive data visualisation, and feedback mechanisms, BOSCA seeks to enhance safety practices in high-risk industrial environments. This approach represents a paradigm shift toward a more proactive, data-driven, and behaviourally anchored model of safety management in the oil and gas sector.

METHODS

The development process of the BOSCA is illustrated in Fig. 1. This process comprises four main phases: requirements, design, implementation, and testing. In the requirements phase, the key elements of BOSCA were reviewed and analysed through expert interviews and an exploration of existing systems to define and refine the application's requirements. The expert interview and prioritisation process that informed the selection of behavioural elements for the BOSCA framework were previously conducted and published in a peer-reviewed article (25). In that study, 40 subject matter experts (SMEs) from four key stakeholder groups; safety practitioners, regulators, academicians and industry managers were selected using purposive and snowball sampling techniques. Eligibility was based on active engagement in occupational safety and health (OSH) with at least five years of experience. The analytic hierarchy process (AHP) was applied to evaluate 18 safety culture sub-elements across psychological, behavioural and situational dimensions. The findings, identified behavioural elements as the most influential, which directly informed the content and structure of the BOSCA application developed in this study.

In the design phase, the system architecture and user interfaces were meticulously designed to create a cohesive structure. Subsequently, the implementation phase involved developing the web/mobile application using Vue.js for the frontend, building a robust database using Supabase, and deploying the model on Netlify to ensure seamless integration and accessibility. Finally, the testing phase encompassed rigorous system and usability testing to validate the effectiveness and user-friendliness of BOSCA. The following subsections elaborate on each phase of the development process, providing further details on the methodologies and technologies employed.

This manuscript focuses exclusively on the conceptualisation, system design, and development process of the BOSCA-PWA framework. A separate study is being undertaken to validate the usability and effectiveness of the application in real-world settings, which will be reported in a subsequent publication.

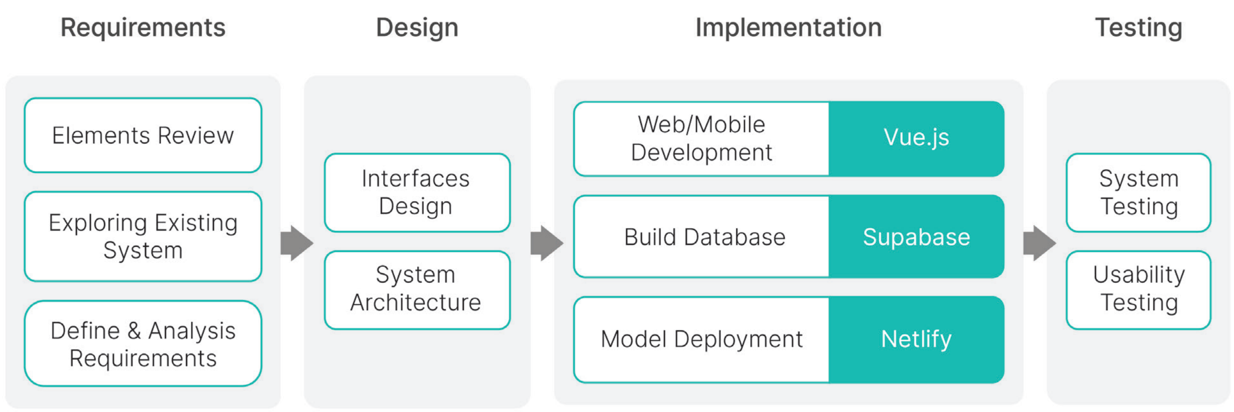

Fig. 1: The development process of the Behavioural Occupational Safety Culture Application (BOSCA).

System Requirements

The first step involved an in-depth exploration of safety culture elements specific to the oil and gas industry. This comprehensive analysis served as the foundation for understanding the key factors influencing safety culture within the sector. A survey was conducted among subject matter experts representing four key stakeholder groups: safety and health practitioners, authorities, academicians, and management. The survey aimed to capture each group's preferences regarding which safety culture elements should be prioritized in the oil and gas industry.

The analysis of survey results indicated that each stakeholder group had distinct preferences for prioritizing safety culture elements. These variations in preferences underscore the need for a flexible and adaptable approach to safety culture enhancement in the industry. After thoroughly analysing the stakeholder preferences, it was determined that behavioural elements should be prioritized. These behavioural elements emerged as the key drivers for enhancing safety culture in the oil and gas industry. The sub-elements of the prioritized behavioural elements are visually represented in Table I.

Table I: Behavioural safety culture elements

Module	Objective	Rationale
Module 1: Management Commitment	To demonstrate and reinforce management's commitment to safety.	This design allows management to efficiently monitor and analyse safety performance, make informed decisions, and take proactive measures to maintain a safe working environment.
Module 2: Safety Commitment	To encourage individual and collective commitment to safety.	This design facilitates efficient and thorough reporting of safety incidents and near-misses, encouraging a proactive approach to workplace safety and fostering a culture of continuous improvement.
Module 3: Safety Ownership	To foster a sense of ownership	Tool for conducting and recording safety audits, facilitating a thorough and systematic approach to workplace safety management.
Module 4: Safety Training	To provide continuous and accessible training.	Accessing and managing safety training materials, promoting continuous learning and improvement in workplace safety.
Module 5: Safety Communication	To ensure clear and effective communication of safety information.	Accessing and managing real-time safety alerts and notifications, ensuring employees stay informed and can respond promptly to safety-related updates.
Module 6: Reward Recognition	To recognize and reward safe behaviour and achievements.	Platform for employees to nominate their peers for safety awards, promoting a culture of recognition and appreciation within the workplace
Module 7: Safety Investment	To demonstrate and track investment in safety.	Interface for employees to submit and track their safety improvement suggestions, fostering a culture of continuous improvement and proactive safety management within the workplace.
Module 8: Safety Competency	To ensure all employees have the necessary skills and knowledge for safety.	For employees to take regular competency assessments, track their progress, and receive feedback to ensure they have the necessary skills and knowledge for safety

After finalizing the safety culture element and the rationale of each element, the functionalities of BOSCA were specified for both actors as portrayed in the use case diagram in Fig. 2. The system described in this study integrates several common use cases that are applicable to both the User and Admin actors, ensuring a cohesive and functional experience for all users. These use cases include essential functions such as registering, logging in, filling out forms, uploading and viewing certificates, receiving notifications, and managing evaluations and hazards. The "Register" use case enables both users and admins to create an account within the mobile application. This process involves entering registration details, which the system validates. Upon successful validation, an account is created, allowing the actor to log in. If the system detects an existing account, an error message is displayed. The "Login" use case provides a secure method for both the user and admin to access the system by entering credentials that the system authenticates against stored data. Successful authentication grants access, while invalid credentials trigger an error message.

In addition, the system includes the "Fill Declaration Form" and "Fill Verification Form" use cases, which allow users to submit and verify required information through forms. Admins are then able to review the submitted data to ensure accuracy. The "Upload Photo" use case enables users to upload images for identification or documentation, with admins reviewing the uploaded photos. The "Pin Location" use case allows users to share their current location, which admins can access for monitoring purposes. This functionality requires location services to be enabled on the user's device. The "Upload Certificate" use case allows users to upload certifications for record-keeping or verification, and the "View Certificate" use case permits both users and admins to access and view these uploaded certificates. The system ensures that certificates are readily available for viewing after they are uploaded. Furthermore, the "Get Notification" use case provides both users and admins with alerts about important updates, tasks, or messages via email, ensuring that key information is communicated effectively. The "View Evaluation" use case allows admins to assess and evaluate users, with the results being made available to users to view their performance outcomes. The system facilitates this process by making evaluation marks accessible once the admin completes the assessment. Additionally, the "Update Hazard" use case enables users to report workplace hazards, which admins can review and manage, playing a crucial role in maintaining workplace safety.

Finally, the "Download Document" use case allows users to download necessary documents, while admins manage the uploading of these documents to the system. The "Fill Suggestion Form" use case enables users to submit suggestions for improvements, which admins can review for potential action or feedback. This suite of use cases is designed to provide a comprehensive and user-friendly experience for both users and admins, ensuring that all critical functionalities are covered while maintaining robustness and reliability in handling various scenarios.

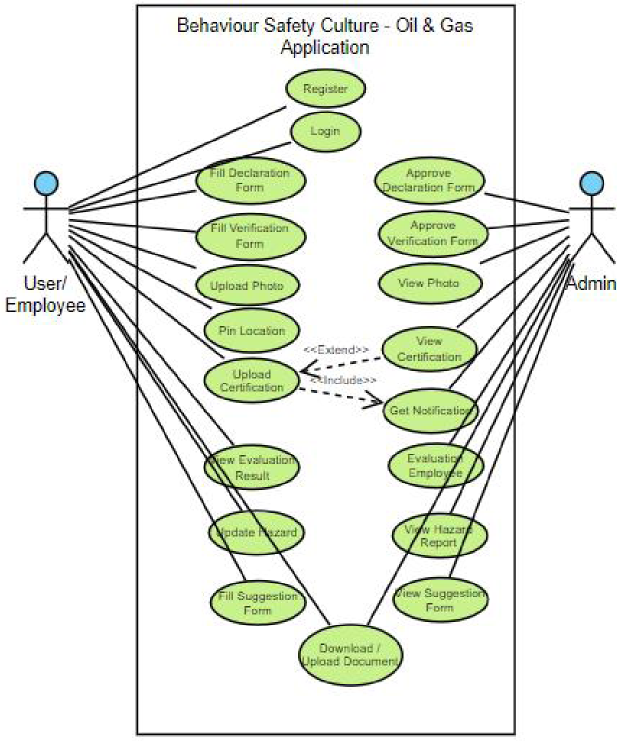

Fig. 2: The diagram depicts the use case diagram for the Behaviour Safety Culture - Oil & Gas Application.

System Architecture

The BOSCA architecture is designed to ensure robust and seamless interactions between users and the system. As illustrated in Fig. 3, the BOSCA architecture is built on a multi-layered approach, integrating various components to deliver an efficient and secure user experience. The user interface layer serves as the primary access point for both users and admins. Users interact with the system via a progress web application, which must be installed on their devices. This application provides functionalities such as account registration, login, form submission, certificate management, and hazard reporting. Admins access the system through a specialized dashboard, allowing them to manage user data, review reports, and perform audits. At the core of the BOSCA is the application layer, which handles the business logic and operations essential to the system's functionality. This layer includes modules for authentication and authorization, ensuring that only authorized users can access specific services. The business logic layer processes user inputs, such as health examination data, field verification results, and safety audit records. The notification module alerts users and admins about important updates, while the data processing module manages tasks like photo uploads and location pinning. The reporting module facilitates the generation of reports, including audit results and hazard identification summaries. All user and system data is stored and managed within the data layer, which comprises a relational database and a file storage system. The database securely stores user profiles, inspection records, training certifications, and hazard reports. The file storage system manages files such as uploaded photos and certificates, ensuring they are accessible when needed.

The integration layer facilitates communication between the user interface and the application layer through an API Gateway. This layer ensures that data flows seamlessly between the front-end application and the back-end services. Additionally, it allows for integration with external services, such as email servers for notifications and third-party systems for enhanced functionality. The BOSCA architecture relies on an independent server, which users remotely connect to via the internet. This setup requires users to have a stable internet connection to access database-related services and perform inspections. The use of an independent server allows for centralized management of data and services, ensuring that all operations are conducted securely and efficiently. This architecture is critical to supporting the BOSCA's mission of promoting a strong safety culture across various industries.

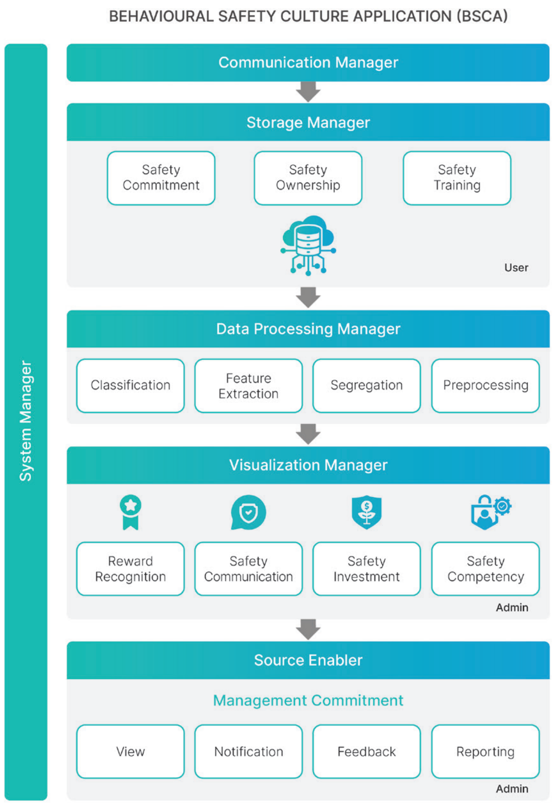

Fig. 3: Illustrates the framework of the Behavioural Occupational Safety Culture Application (BOSCA).

Database

The BOSCA database structure was meticulously designed using a class diagram in unified modelling language (UML) notation. The class diagram serves as a graphical representation that captures the structural components of the database, including classes, attributes, and relationships, providing a detailed overview of the application's data organization. Fig. 4 depicts the Entity-Relationship Diagram (ERD) for the BOSCA. This diagram outlines the key entities within the application and the relationships between them, providing a comprehensive overview of the data structure and interaction mechanisms.

The user entity contains attributes such as user ID, user name, user email, user phone no, user role, and user pass. This entity is responsible for user registration and login processes within the system. The admin entity, which includes attributes like admin ID, admin name, admin email, admin phone number, and admin pass, provides higher-level access for managing user accounts and sending notifications. The login entity manages the authentication process and records login sessions with attributes such as login ID, user ID, login time, logout time and admin pass, including methods for user authentication and sending notifications. The incident report entity represents incidents reported within the system and includes attributes such as report ID, incident date, incident type, incident description, incident location, and incident reported by, allowing users to file incident reports. The observation entity captures observations made by users, with attributes like observation ID, observer ID, observed behaviour, observation time, observation location and observation comment and includes methods to log observed behaviours. The behaviour entity details specific behaviours observed or recorded, including behaviour ID, behaviour type and behaviour description and is linked to observation logs for categorizing and managing behaviour-related records. Additionally, the safety audit entity manages safety audits, with attributes such as audit ID, audit date, audit findings and action required, supporting the documentation of findings. The training entity represents the training programs scheduled and completed, with attributes such as training ID, training name, training date, trainer ID and training completion status and includes methods for scheduling training sessions and recording completion. The notification entity manages notifications within the system, with attributes like notification ID, user ID, notification date and notification message and is responsible for sending notifications to users.

Firebase was utilized to build the database due to its suitability for real-time applications (26-28). Its integration enables seamless synchronization of data across devices, supporting critical functionalities such as incident reporting, safety audits, training management and user notifications. This database structure enhances the system's efficiency and adaptability to changing requirements, providing a solid foundation for the BOSCA application's operations.

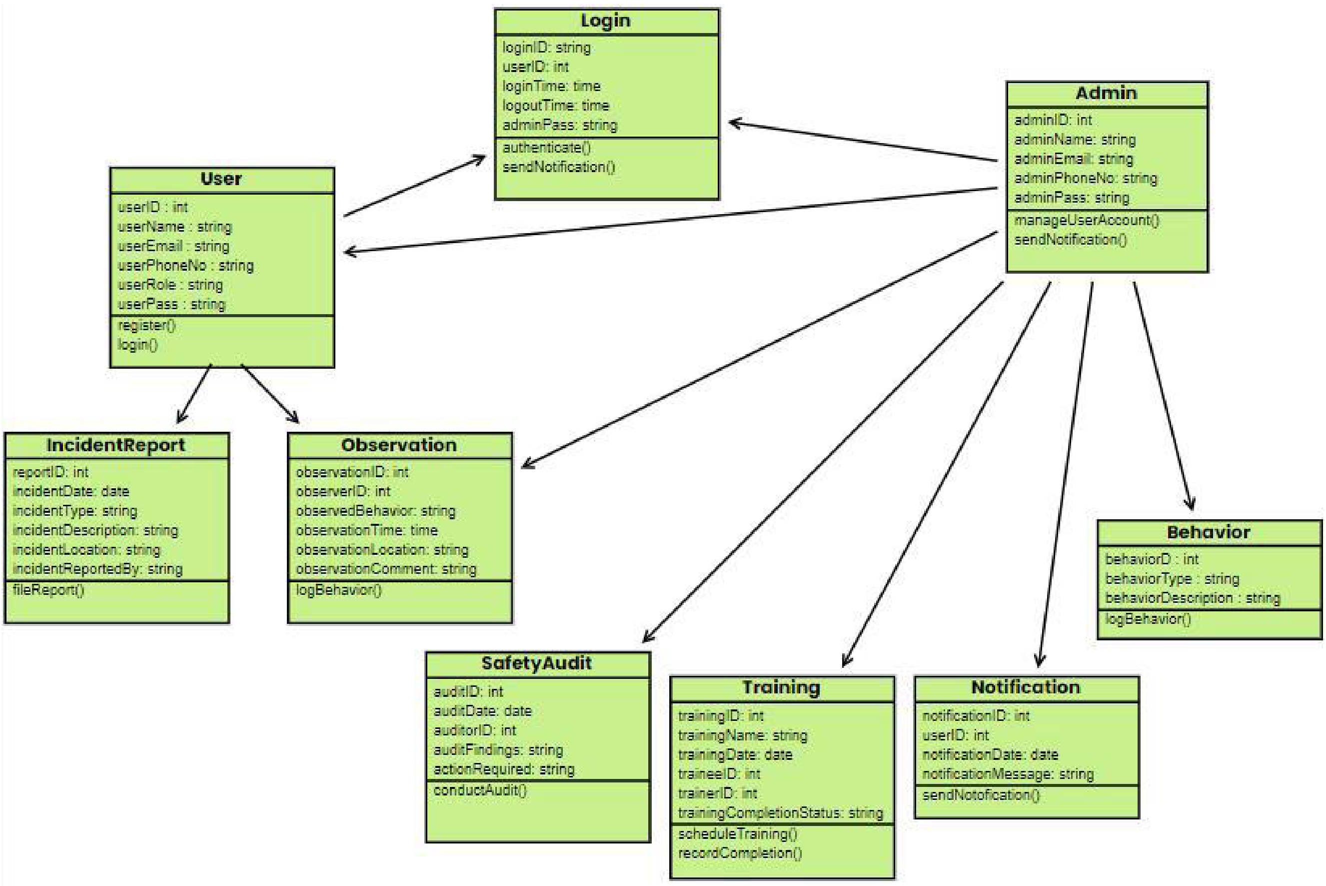

Fig. 4: depicts the Entity-Relationship Diagram (ERD) for the Behavioural Occupational Safety Culture Application (BOSCA).

Application Development

The real-time monitoring tool for safety culture behaviour in the oil and gas industry was developed with a focus on cross-platform accessibility and efficient data management. Initially built using Flutter, a leading cross-platform framework by Google, the application was designed to create natively compiled apps for both iOS and Android from a single codebase. However, considering the versatility and benefits of Progressive Web Applications (PWAs), the mobile application can also be substituted with a PWA, which offers similar advantages with additional flexibility. User Interface (UI) Design was prioritized to ensure a seamless and intuitive experience. The UI was developed using Flutter's widget library, but with a PWA, the design could be further optimized to work directly within a web browser across multiple devices, including desktops. This would eliminate the need for users to download and install the application, while still offering an app-like experience when added to the home screen on mobile devices.

Core features such as real-time data collection allow field inspectors and safety officers to submit observations directly from the field, with data immediately uploaded to a central database. Geolocation tracking, initially integrated using Google API, remains a key feature in both the mobile app and the PWA, ensuring precise location tagging of reports. The PWA can also support offline functionality, enabling users to record observations without internet connectivity and synchronize data once the connection is restored. The PWA's automatic update feature ensures that all users are always using the latest version of the application without the need for manual updates, further simplifying maintenance. Additionally, the application implements robust security measures, including end-to-end encryption and secure user authentication, whether accessed as a mobile app or a PWA. On the backend, the application is integrated with a centralized server that ensures high availability and scalability, capable of handling large volumes of data typical in the oil and gas industry. The server communicates with the application via RESTful APIs, ensuring efficient data exchange, regardless of whether the front-end is a native mobile app or a PWA.

Frontend and Backend Architecture

The BOSCA application was developed with a clear distinction between frontend and backend functionalities. The frontend designed using Vue.js and Flutter delivered the user-facing experience, including modules for hazard reporting, training, feedback notifications and competency tracking. These modules were optimised for cross-device accessibility and responsive interaction. The backend, developed using Supabase and Firebase, managed secure data processing, API connections, user authentication and storage. It supported key backend services such as incident record logging, notification delivery, and reporting module integration. User testing during the validation phase focused solely on the frontend modules. Participants were engaged in evaluating interface usability, functionality access, and task flow navigation, while backend operations were tested internally to verify performance, data handling and system integrity.

Ethics Statement

The study was approved by the Research Ethics Committee (REC) of UiTM under the reference number: REC/07/2023 (PG/MR/251) dated on 21st Jul 2023. The approval duration was July 2023 until September 2024.

RESULTS

The results of the BOSCA framework showcase a cohesive set of interfaces, each meticulously designed to address specific facets of safety culture within the oil and gas industry. Fig. 5 illustrates the BOSCA key interfaces, designed to enhance safety culture in the oil and gas industry. The figure presents six main interfaces: audit, training, reward recognition, incident reporting, competency, and communication alerts. Each interface plays a distinct role, from conducting and reviewing safety audits to providing interactive training, recognizing safe behaviours, streamlining incident reporting, assessing employee competencies, and delivering real-time safety alerts. Together, these interfaces create a comprehensive and user-friendly platform, reinforcing proactive engagement and effective communication to promote a strong safety culture.

The audit interface, as shown in Fig. 5A, is structured to facilitate detailed and systematic safety audits within the application. It includes modules for conducting audits and generating reports, enabling users to thoroughly review audit scores and identify potential areas for improvement. The intuitive design allows users to easily log non-conformances and document their findings. This proactive identification of safety issues through ongoing monitoring strengthens organizational safety culture by promoting consistent and rigorous audit practices. The training interface, depicted in Fig. 5B, aims to enhance employees' safety competencies by providing access to a wide range of training materials relevant to the oil and gas industry. Users can engage in interactive training sessions that cover various safety topics, thereby fostering continuous learning. The structured approach allows users to track their progress across different training modules, emphasizing the importance of skill development. This feature is essential for upholding high safety standards and equipping employees with the knowledge necessary to perform their duties safely.

The reward recognition interface, illustrated in Fig. 5C, incentivizes safe behaviours by acknowledging and rewarding employees who exhibit a strong commitment to safety. Managers can nominate and recognize individuals or teams for their safety contributions through a system for tracking and managing rewards. By promoting a culture of recognition, this feature aligns individual motivations with organizational safety objectives, encouraging employees to prioritize safety in their daily operations. The incident reporting interface, as shown in Fig. 5D, provides users with a streamlined process for reporting safety incidents. It includes fields to capture detailed information such as the type of incident, location, time, description, image evidence, and severity. The user-friendly design facilitates prompt and accurate incident reporting, which is crucial for timely investigations and the implementation of preventive measures. This interface promotes a transparent safety culture by ensuring that incidents are managed efficiently and transparently.

The competency interface, depicted in Fig. 5E, focuses on assessing and monitoring employees' safety competencies. It features tools for evaluating safety skills, tracking certifications, and identifying areas for improvement. Users can view their competency levels across various safety areas, providing them with a clear understanding of their strengths and potential growth opportunities. This feature reinforces the importance of continuous skill development and ensures that employees maintain the necessary competencies for their roles. The communication alerts interface, shown in Fig. 5F, enhances real-time communication regarding safety-related matters. It enables users to receive alerts about critical safety information, such as hazards, policy updates, or emergency notifications. Alerts are delivered promptly to ensure that all employees are informed and can respond appropriately. This feature supports a proactive safety culture by ensuring the swift and effective communication of essential safety information across the organization.

The BOSCA framework effectively integrates these interfaces to provide a comprehensive platform for promoting and sustaining a strong safety culture. Each interface contributes to reinforcing a proactive and transparent approach to safety management, empowering users to engage actively in safety practices within the organization.

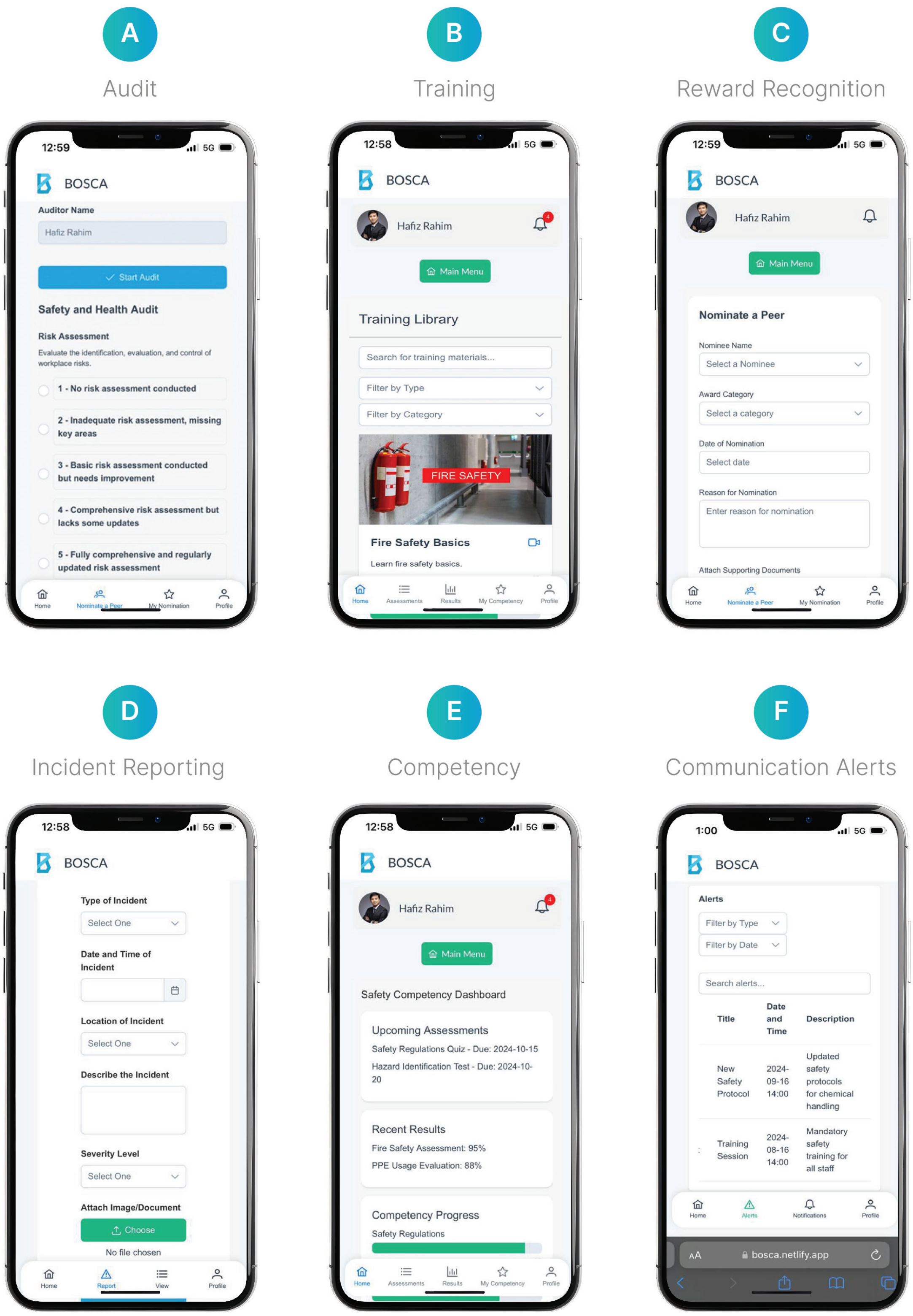

Fig. 5: Illustrates the key interfaces of the Behavioural Occupational Safety Culture Application (BOSCA), designed to enhance safety culture in the oil and gas industry. The figure presents six main interfaces: (A) Audit, (B) Training, (C) Reward Recognition, (D) Incident Reporting, (E) Competency, and (F) Communication Alerts. Each interface plays a distinct role, from conducting and reviewing safety audits to providing interactive training, recognizing safe behaviours, streamlining incident reporting, assessing employee competencies, and delivering real-time safety alerts.

The visualization manager within the BOSCA framework serves as the central component that consolidates and presents safety data in a cohesive and meaningful format, acting as an interactive hub for managing the four key elements: reward recognition, safety competency, safety communication, and safety investment (Fig. 6). Its primary function is to transform raw data into actionable insights through various visualization techniques such as dashboards, graphs, and charts, providing real-time updates that allow safety managers to monitor trends in reported incidents, track employee training completion rates, and oversee the distribution of safety rewards. This interactive and centralized visualization approach facilitates seamless monitoring of key safety performance indicators (KPIs), enabling stakeholders to assess the effectiveness of different safety initiatives and implement targeted interventions based on clear patterns and areas needing improvement. The visualization manager supports real-time decision-making and fosters transparency by making critical information accessible to relevant stakeholders, empowering them to generate customized reports and drill down into specific data details. Additionally, it plays a vital role in long-term strategic planning by identifying trends and correlations that guide future safety investments and policy changes, thereby promoting a data-driven and proactive approach to safety management. By synthesizing and presenting critical information effectively, the visualization manager reinforces continuous improvement, accountability and the proactive management of safety culture within the organization.

The reward recognition component within the BOSCA framework is designed to incentivize and acknowledge safe behaviours and contributions to safety culture within the organization (Fig. 6). This component enables managers to systematically track and reward individuals or teams who demonstrate a strong commitment to safety, aligning individual motivations with the organization's safety objectives. The system allows managers to nominate employees for their proactive safety actions, document their contributions, and recognize them through a structured rewards program. By offering a transparent and systematic approach to recognition, this component fosters a culture of appreciation where safe behaviours are consistently encouraged and reinforced. The rewards, which can be both tangible and intangible, are strategically designed to motivate employees to adhere to safety protocols and go beyond compliance. Moreover, the reward recognition component includes features for tracking and managing the rewards distributed, providing a clear record of the organization's commitment to reinforcing positive safety practices. This structured approach not only enhances individual and team engagement but also contributes to a collective focus on upholding high safety standards throughout the organization. Through this alignment of recognition with safety goals, the reward recognition component plays a crucial role in promoting a proactive and safety-conscious work environment.

The safety competency component within the BOSCA framework is focused on assessing, monitoring, and enhancing the safety-related skills and qualifications of employees within the organization. This component is designed to provide tools for evaluating employee competencies through periodic assessments and tracking of safety certifications. By maintaining a centralized record of competencies, the system ensures that employees are equipped with the necessary knowledge and skills to perform their roles safely, in alignment with the organization's safety standards. The safety competency interface offers features that allow users to view their competency levels across various safety domains, identify areas requiring improvement, and access additional training resources if needed. This continuous monitoring supports a dynamic and adaptive safety culture, where skill gaps can be promptly identified and addressed to minimize risks. Moreover, it enables management to make informed decisions regarding workforce readiness and the allocation of training resources. By promoting a culture of continuous learning and development, the safety competency component reinforces the importance of staying up-to-date with industry best practices and safety protocols, ultimately contributing to a safer and more competent workforce. Through this structured and proactive approach, the BOSCA framework not only ensures compliance with safety standards but also fosters a culture of ongoing improvement and preparedness in high-risk environments (Fig. 6).

The safety investment component within the BOSCA framework plays a crucial role in supporting strategic planning and resource allocation for safety initiatives within the organization. This component is designed to provide insights into the effectiveness of safety investments by tracking and evaluating expenditures related to safety programs, equipment, training, and other critical areas. By integrating financial data with safety performance indicators, the safety investment component allows management to make informed, data-driven decisions on where to allocate resources to achieve the greatest impact on overall safety performance. This feature helps identify the most effective safety initiatives and areas requiring additional investment, ensuring that resources are directed toward programs and measures that significantly enhance safety outcomes. It also enables organizations to assess the return on investment (ROI) for various safety measures, thereby optimizing spending to align with safety goals and regulatory compliance. The component's detailed analysis capabilities support ongoing evaluation and refinement of safety strategies, encouraging a proactive approach to improving safety culture through targeted investments. By promoting transparency and accountability in resource management, the Safety Investment component reinforces the organization's commitment to prioritizing safety and allocating the necessary resources to maintain high standards. This strategic focus not only helps organizations achieve their safety objectives but also fosters a culture where safety is viewed as a valuable and essential investment in the workforce's well-being and operational resilience (Fig. 6).

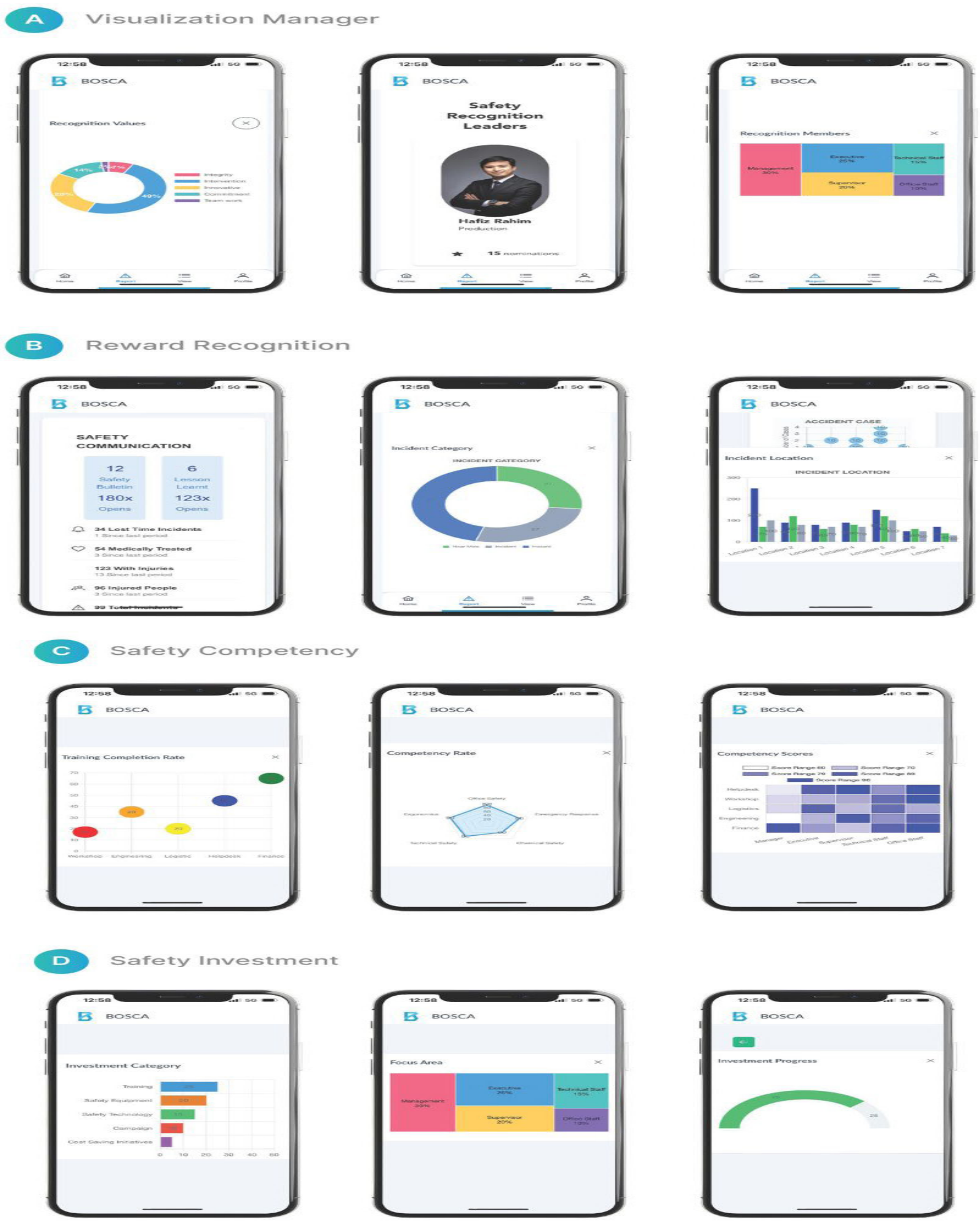

Fig. 6: The illustration presents the key elements managed by the Visualization Manager within the Behavioural Occupational Safety Culture Application (BOSCA). This figure highlights four primary components: (A) Visualization manager; (B) Reward Recognition, (C) Safety Competency and (D) Safety Investment.

Validation Scope
The BOSCA framework underwent internal validation during the development process, which included system-level testing and simulated user walkthroughs to verify the functionality, stability and integration of its features. This testing ensured that modules such as hazard reporting, training access and communication alerts performed reliably across different devices and user roles. External validation including pilot deployment, real-world user interaction and behavioural impact analysis was not included within the scope of this development-focused manuscript. A separate validation study is currently in progress to evaluate the BOSCA application in actual operational settings and will be reported in future publications.

DISCUSSION

Benefits of BOSCA Framework
Our framework for real-time monitoring of behaviour and safety culture in the oil and gas industry integrates several critical methods to ensure comprehensive and accurate data capture. The framework systematically documents safety incidents and activities through electronic logs and manual reports, which are periodically reviewed to identify and analyse trends. It also leverages online surveys and mobile apps to gather employee perspectives on safety culture, collected at regular intervals (monthly or quarterly), providing qualitative insights into the effectiveness of safety programs. Additionally, the framework tracks training and compliance records to monitor participation in safety training and adherence to safety regulations, ensuring records are up-to-date and reflective of ongoing efforts. Continuous monitoring of health and safety metrics, coupled with periodic assessments, enables real-time evaluation of safety performance and ensures adherence to established standards.

A key component of our framework is the user interface design, which ensures that stakeholders can effectively access and interpret real-time data. The user interfaces are designed to be intuitive and accessible, featuring dashboards that display critical safety information clearly and organized. Key features include customizable views, real-time data updates, and visualizations such as graphs and heat maps to highlight trends and anomalies. Usability considerations such as simplicity of navigation, readability of data and responsiveness across various devices and screen sizes are prioritized. The interface is developed with input from end-users to ensure it meets their needs and preferences, facilitating quick and accurate decision-making. Accessibility features, including adjustable font sizes and color schemes, accommodate diverse user needs, ensuring that critical safety information is effectively communicated to all stakeholders. This user-centered design approach enhances the usability of the system, promoting efficient monitoring and proactive management of safety culture.

Practical Implications and Future Work
It is important to note that while the current study focused on internal system development and validation, further research will assess BOSCA's usability, engagement levels, and behavioural outcomes through external validation in field conditions. The BOSCA application, by enabling real-time monitoring and feedback, addresses critical gaps in traditional safety systems, aligning with findings from prior studies on behaviour-based safety frameworks and technology-enabled safety systems (29-31). This capability allows organization to address potential safety issues proactively, thereby reducing the risk of incidents and enhancing overall safety performance (14). The ability to provide instant feedback and actionable insights not only empowers managers to make informed decisions quickly but also fosters a more engaged and safety-conscious workforce (32). Furthermore, the framework's comprehensive approach, which includes robust data collection, processing, and visualization through an intuitive interface. This integration of advanced technology with traditional safety management approaches marks a significant shift towards more dynamic and responsive safety management in high-risk industries like oil and gas (33-35). The implications of this framework extend beyond immediate safety improvements, contributing to the long-term sustainability of safety practices and the cultivation of a proactive safety culture.

Challenges and Implementation Considerations
However, implementing this framework is likely to encounter challenges, particularly in integrating with existing systems, ensuring data privacy, and managing the complexity of real-time data processing. Integration strategies involve developing robust APIs and compatibility solutions to facilitate seamless data exchange with legacy systems, ensuring a smooth transition and accessibility across platforms (36-38). Data privacy is addressed by implementing comprehensive security measures, including end-to-end encryption and access controls, to safeguard sensitive information (39). Complexity management is handled by utilizing scalable technologies such as cloud computing and distributed databases, along with adaptive algorithms capable of dynamically processing large volumes of real-time data, enabling timely and accurate decision-making (40-42).

Limitations and Strengths

One of the primary limitations of the study lies in the integration challenges associated with implementing the BOSCA within existing infrastructure in the oil and gas industry. The complexity of legacy systems may hinder the seamless integration of the BOSCA, requiring significant customization and potentially increasing implementation costs and time. Another limitation is the potential resistance from end-users who are accustomed to traditional safety management practices. The shift to a real-time, behaviourally-driven monitoring system might require extensive training and a change in mindset, which could pose challenges in adoption. Additionally, while the BOSCA is tailored for the oil and gas industry, its specific focus on this sector may limit its applicability and effectiveness in other industries without substantial modifications.

Despite these limitations, the study has several key strengths. The BOSCA represents a significant advancement in safety management by integrating real-time monitoring with a comprehensive behavioural framework, which is not commonly found in existing safety management systems. The inclusion of eight critical sub-elements; management commitment, safety commitment, safety ownership, safety training, safety communication, reward recognition, safety investment and safety competency to ensures a holistic approach to enhancing safety culture. Furthermore, the application's design adheres to essential principles such as visibility, feedback, constraints, consistency, and affordance, resulting in an intuitive and user-friendly interface that promotes active engagement from all stakeholders. The real-time capabilities of the BOSCA allow for immediate feedback and proactive intervention, which are crucial in preventing incidents and maintaining a high standard of safety in the high-risk environment of the oil and gas industry.

To address the identified limitations, future versions of BOSCA will explore enhanced API integration with legacy systems, improved modularity to adapt across industries, and expanded user onboarding features including gamified training and adaptive interfaces. These improvements aim to enhance system interoperability, reduce user resistance, and broaden BOSCA's applicability beyond the oil and gas sector.

CONCLUSION

The development of BOSCA marks a significant step forward in digital safety management for the oil and gas industry. By embedding critical behavioural elements into a cohesive digital framework, BOSCA provides a practical solution for strengthening proactive safety culture in high-risk settings. Built on user-centred design principles and cross-platform accessibility, the system supports continuous monitoring, timely feedback and structured interventions. While these results support BOSCA's functional readiness, full-scale validation in operational environments will be reported in future studies.

Despite its advantages, BOSCA's implementation may face challenges related to system integration and data privacy. Future development will focus on refining predictive analytics, broadening compatibility across industries, and enhancing user onboarding through adaptive features. Overall, BOSCA contributes to the ongoing evolution of safety culture management by offering a scalable, responsive, and behaviourally-driven framework. It lays the groundwork for a more engaged, data-informed approach to managing safety in complex industrial operations.

Author contribution

The conceptualization and methodology for the study were developed by HR, RD, NCD, MIMN, and AAA. The original draft of the manuscript was written by HR, RD, NCD, MIMN, and AAA. All authors contributed to the review and editing of the manuscript.

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