Collaborative hazard control: designing a digital fire control center for enhanced safety on ships

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Figure 1: Interface of an Digital Fire Central with a adjustable heavy duty 55" touchscreen table

ABSTRACT

Every day, thousands of vessels of varying sizes traverse the world's seas, posing significant risks of ship loss, cargo damage, and loss of crew lives due to onboard fires, which can rapidly escalate beyond control. With the ongoing advancement towards highly automated or autonomous ships, the challenge of ensuring an adequate number of experienced firefighters onboard will diminish. Consequently, enabling external firefighting personnel or operators stationed in

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control rooms to oversee the overall situation becomes crucial in guiding less-experienced crew members in fire containment and prevention efforts. This necessity for future autonomous vessels and current manned ones underscores the importance of enhancing shared situational awareness and establishing platforms for informed decision-making and communication.

Ships comprise multiple decks housing various sensors, firefighting equipment, and cargo with different risk classifications. For fire chiefs and control room operators stationed on the ship bridge or on land, early detection of fires and the implementation of appropriate measures to mitigate risks are essential. This paper presents the design of a digital fire central (DFC), developed through a human-centred design process and evaluated by three fire chiefs aboard Roll-on-Roll-Off (Ro-Ro) ships. The primary focus lies in detailing the design process and presenting initial insights from user evaluations.

CCS CONCEPTS

• Information systems → Collaborative and social computing systems and tools; **• Human-centered computing → Empirical studies in interaction design**; **Empirical studies in HCI**.

KEYWORDS

Human Centred Design, maritime safety, hazard control, fire safety, collaborative work

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1 INTRODUCTION

In its Safety and Shipping Review, Allianz [1] highlights the significant number of ships lost in recent years and examines the root causes of these incidents. Between 2013 and 2022, a total of 807 ships were reported lost worldwide across all categories, with 116 of these losses attributed to fire or explosion. Specifically, roll on-roll off (Ro-Ro) vessels accounted for 37 casualties, while passenger vessels contributed to 70 casualties.

The report highlights that cargo poses the greatest fire risk, particularly due to factors such as mislabelled and improperly packed cargo, as well as the carriage of electric vehicles and lithium-ion batteries. These elements significantly increase the potential for fire incidents at sea, highlighting the critical importance of robust safety measures and improved fire-fighting capabilities within the maritime industry. In this context, Ro-Ro ferries are of particular safety concern as they carry both cargo and passengers. Prominent examples include the Norman Atlantica incident in 2014, where a fire starting at the car deck resulted in several deaths and the complete destruction of the ship. In 2011, there was an electric vehicle that ignited aboard Pearl of Scandinavia and set fire to surrounding cargo [9].

Having well-trained and experienced crews on board ships is critical to mitigating fire risks. However, recent trends indicate a decline in crew experience and numbers due to factors such as globalisation and economic pressures [5], the recruitment of workers from low-wage countries [16], and technological advances such as highly automated ships and changes in training practices, resulting in skills and competence gaps [12]. In workplaces where people from different cultures work together, communication barriers can arise, affecting ship safety [6]. Espevik's research [4] shows that unfamiliar or inexperienced teams are often less efficient at coordinating strategies, making them less effective in stressful situations and unfamiliar environments, even when individuals have expertise in their tasks. The presence of less experienced crews can increase the likelihood of human error [10], exacerbating the challenges of managing fire and other hazards on ships.

Crises are typically managed by a network of actors rather than by individual efforts alone. Successful crisis management depends on each actor in the network sharing relevant information and working together towards a common goal [13]. Fostering effective communication and collaboration between crew members and relevant stakeholders is therefore critical to effectively managing and mitigating risks, including those posed by fires and other maritime hazards.

Previous studies (SEBRA [3] and FIRESAFE [11]) highlighted the fire alarm system interfaces as an area in particular need of attention within the sphere of fire-safety-related design. Issues stemming from poorly designed fire alarm panel interfaces could play a role in significant delays in fire detection and firefighting efforts.

In this paper a concept of a Digital Fire Central (DFC) is presented and user-tested. The concept adressses the need for more efficient fire detection and decision-making systems on ships. The design is based on the findings from the ethnographic observations onboard Ro-Ro ferries. The description of the DFC in this paper is a summary of a project progress report of the authors on the website of Lashfire [14]. The DFC aims to integrate critical information such as fire plans, sensor and alarm statuses, location of firefighting equipment locations, and cargo details into a single interface. This consolidation is designed to make crucial information more accessible and understandable, especially under the stressful conditions of a fire emergency. The goal should be to provide one big picture for each actor in the network as well as actors outside the network supporting the less experienced actors. Users have expressed a desire for intuitive interfaces that minimize the risk of operator error and potential accidents, stressing the importance of ease of use to prevent additional stress during emergencies.

In pursuit of enhancing the fire safety onboard ro-ro ships, the EU funded LASH FIRE project aims to address the problem holistically. The project consist of altogether 11 work packages which are touching into legislative, operational and technical aspects amongst others [14]. This article focuses on the work done as part of the work package *Inherently Safe Design* which aims to reduce the risk of human error by improved design of tools, environments and methods [14].

1.1 Purpose of the study

The design of the DFC was driven by the need to improve access to critical firefighting information, such as fire location and monitoring, by integrating available data into easy-to-understand displays. In addition, the design aimed to facilitate effective firefighting operations, including the activation of drenchers, by offering important details for important decisions and allowing centralized management of crucial functions from one place.

To evaluate the effectiveness of the DFC in improving firefighting capabilities on Ro-Ro vessels, a user-centred testing approach was adopted. This approach sought to answer the central questions:

- "What could a holistic DFC look like?"
- "Does the DFC concept help to manage fires more efficiently?"
- "How can the DFC concept support autonomous shipping?"

1.2 Contribution

This publication introduces the concept of a DFC, developed through a human-centered design process. It aims to identify gaps and limitations in the current version and gather suggestions to inform future design iterations and refinements.

By prioritizing user needs and feedback, the testing process evaluates if and how the DFC design closely aligns with the operational requirements and challenges faced by firefighters on Ro-Ro vessels. The following section provides the background for the presented research, detailing the rationale and context for the development of the DFC.

2 BACKGROUND

2.1 The Situation Today

An important basis for the development of the DFC was to observe the situation of fire detection and management onboard of Ro-Ro ships today. By analysing the video material described in the LASH FIRE report [2], different fire management techniques were seen by the authors during ethnographic observations on board ships. In one case the detection of heat or smoke by an alarm sensor initiated a thermo printer to print out the number of the respective sensor. This would lead the officer on watch to refer to a manual in order to identify and locate the sensor. A runner would be sent to verify if there is a fire is present. The runner would then communicate whether or not a fire is present back to the bridge. The process of locating, verifying and communicating a potential fire to the bridge was observed to take around 15 minutes in its current state. Further fire management is mostly done by the use of paper maps and verbal communication. This was observed to result in incoherence between crew members and unawareness of the current fire situation onboard.

Observations on other ships revealed alternative fire management concepts, such as fire panels equipped with LEDs or fully digital panels displaying temperature and smoke particle levels in specific sections. Despite these variations, several common gaps and challenges were identified:

- Lack of shared situational awareness among all involved members, attributed to the use of paper maps or limited access to digital interfaces.
- Lengthy time required to confirm a fire and initiate hazard control measures.
- Disparate information and control points across different locations, necessitating extensive communication.
- Communication difficulties arising from reliance on VHF radio, leading to misunderstandings.
- Some roles necessitating management of multiple VHF devices with distinct channels, resulting in information fragmentation.
- Limited understanding of the fire's size and development from distant locations such as the bridge, engine room, or external control rooms.

2.2 Rationale for the DFC design

The design of the DFC is based on extensive studies carried out during the Lash Fire project, which focused on firefighting exercises on board Ro-Ro vessels. These studies identified critical needs such as efficient event logging, fire tracking and information dissemination within firefighting operations. The overall objective was to strengthen the decision-making process on the ship's bridge.

A key objective of the DFC design was to facilitate real-time assessment of fire-fighting operations. For example, it provides essential data on the activation and effectiveness of drencher systems, giving insight into fire spread, intensity and the results of drencher activation. This functionality is intended to support that bridge personnel can make timely, informed decisions to optimise their response to evolving fire scenarios.

Through the initial observations, it was observed that effective communication is paramount in managing fire emergencies. Based on this insight, the DFC integrates communication tools and functionalities to improve the exchange of information between bridge personnel, the Engine Control Room (ECR) and the fire-fighting teams. Real-time updates on the progress of the fire are shared between the relevant parties, promoting a common understanding and facilitating a coordinated response. By streamlining communication channels and providing timely updates, the DFC contributes to improved situational awareness and more effective firefighting operations.

2.3 Visualisation principles

The visualisation principles of the DFC emphasise clarity, accessibility and efficiency in emergency situations. In addition to alarm-related functions, the interface integrates countermeasure controls. A key component is the interactive deck plan, which combines traditional paper fire plans with digital capabilities to provide a comprehensive view of the ship's layout and fire-related elements. This feature allows users to navigate between decks and switch to a 3D perspective for a detailed understanding of fire locations and affected areas.

The mimic fire panel displays detectors directly on the ship's layout, providing a visual method of quickly identifying and locating fires, as opposed to text-based alarm systems. Alarm management is facilitated by clear indications of sensor activation and alarm history, helping operators to quickly pinpoint the origin of the fire and track its progress. In addition, the visual cues have been designed to be prominent without overwhelming the operator, taking into account the low light conditions typically found on ship's bridges, where maintaining night vision is critical.

The visual strategy prioritised intuitive navigation, visual clarity and the prominence of critical information, focusing on three primary elements:

(1) **Fire Plan Overview:** Provides a detailed view of one deck at a time, highlighting emergency equipment locations, alarm activation and heat and smoke dispersion through data overlays. Standardised IMO compliant symbols ensure consistency and clarity (IMO IA847E [8] & IMO Resolution A.654[7]).
(2) **Control Panel:** Aggregates all the necessary controls for fixed firefighting systems, enabling rapid activation of emergency response systems such as ventilation, fire doors, pumps and drenchers. This arrangement aims to minimise the time to action and reduce the cognitive load on the operator.
(3) **Historical Fire Event Review:**Provides insight into past fire events to facilitate pattern recognition and situational analysis. It displays logged actions, alarms and communications to help operators understand the progression of previous incidents.

3 METHODOLOGY

In this section the design process of the DFC, which involved an extensive investigation into the workflows, communication patterns, and tools utilized in hazard control on ships. This investigation is briefly outlined in the following subsection, which is followed by a description of the DFC design components.

3.1 Investigating the Domain and Context

To gain deeper insights into the dynamics of fire incidents and fire drill procedures aboard RoRo-Ships, a video-based ethnographic approach was employed. Selected crew members were equipped with chest-mounted action cameras (GoPro) during multiple fire drills. This method was chosen to obtain an unbiased perspective on the workflows, communications, and tools utilized in managing fire hazards on board. Following the drills, the recorded videos were synchronized and subjected to detailed analysis. This analysis aimed to discern the inter-group communication dynamics onboard, as well as the utilization of information artifacts, systems, and controls in detecting and addressing fire incidents. Further details on this part can be found in [2].

3.2 DFC Concept Design

The design and development of the DFC concept is based on a Human-centered design approach. Insights from the domain and context investigation were actively used to inform the design drafts of the concept. Small-scale testing and feedback on prototypes of increasing fidelity refined the concept. The initial prototypes stretched from paper prototypes to first digital versions with clickable elements. The final prototype tested in this paper is a full-scale mock-up with further refinements of the concept presented in [9].

3.3 Usability Testing

In this section the setup of the study is described in detail, which includes the participants and the experimental setup.

3.3.1 Participants. The usability testing involved four operators (Table 1, one female and three males, from a major European ferry operator. All participants held the role of fire chief within the organization and were experienced in their field. Two participants worked on Ro-Pax vessels, one on Ro-Ro vessels, and one on cargo ships with prior experience on Ro-Pax vessels. Each participant voluntarily consented to participate in the study.

Table 1: Participants demographics

Participant	Gender	Professional Role	Experience in Years
1 (Pilot Study)	male	Chief Officer & Fire Leader	9
2	male	Chief Officer & Fire Leader	6
3	male	Chief Officer & Fire Leader	9
4	female	Chief Officer & Fire Leader	11

3.3.2 Experimental Setup. The pilot test was conducted in our organization's laboratory, while the actual user tests took place at the headquarters of a major European ferry provider. The physical and digital prototypes were set up in laboratory or meeting rooms. The physical setup (Fig. 2 included a 55-inch touch display mounted on a self-developed and built frame and table. The table was height-adjustable from 90 to 180 cm, and the screen angle could be adjusted from 0 to 90 degrees. Two 24-inch screens were installed above the DFC system to display CCTV footage. The fully functional prototype was created using Axure RP 10, and the scenario was based on a regular fire drill of the ferry provider. During the simulation, each participant was provided with equipment to capture their actions, interactions, and focus during the experiment. The equipment included a chest-mounted action camera (GoPro) to record all activities, a Pupil Labs - Pupil Core eye tracker to monitor the participant's focus on different elements throughout the stages, and a wireless microphone pack to capture verbal expressions and communications. The Officer on Watch role was equipped with a camera mounted on their chest to record their perspective. All video and audio feeds, as well as screen capture, were combined using a Black Magic ATEM Mini Extreme ISO device. These feeds were then live-streamed to a nearby meeting room, allowing the research team to observe the user testing in real-time and perform their roles based on provided role cards. Communication between participant and roles during the simulation was facilitated using VHF radios, replicating the communication methods commonly used on ships. The simulation was operated on a powerful computer, which also provided the CCTV feeds from the deck, ensuring a realistic testing environment.

The experiment consisted of multiple phases and included following parts:

(1) **Welcomed and Introduction:** Participants were welcomed and briefed on the experiment's agenda. They were informed of the voluntary nature of their participation and signed an informed consent waiver.
(2) **Training and Familiarization:** During the training and familiarization phase, participants received an introduction to the DFC's functionalities and had 10 to 15 minutes to explore the prototype. During this phase, they were encouraged to vocalise their initial thoughts (think aloud).

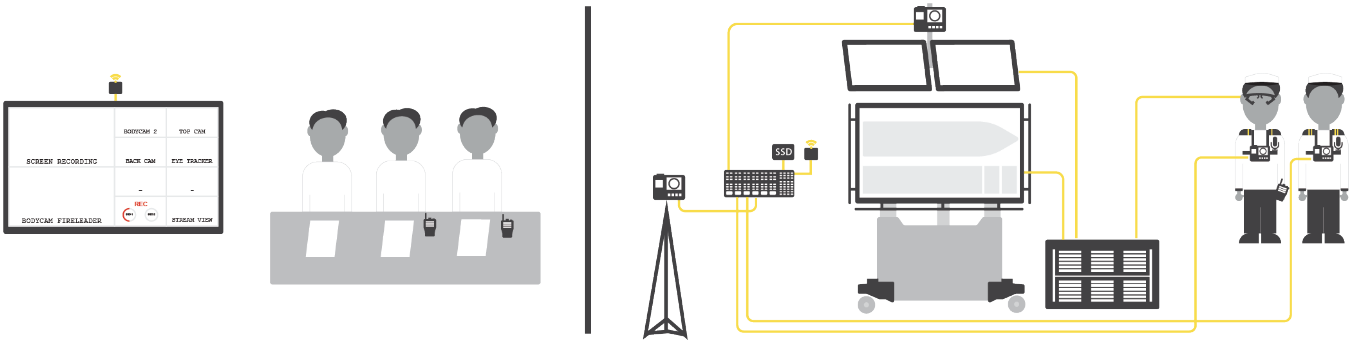

Figure 2: The illustrations shows the experimental setup, with the researchers observing and playing their roles (left) and the setup in the simulated control room (right).

(3) **Simulation- and Role-play-based user testing:** The user testing took place in a simulated control room setup, where participants engaged in a simulated fire scenario. They interacted with the DFC and received verbal instructions based on a protocol. Access to simulated CCTV footage and VHF radios for communicating with firefighting teams and other crew members were provided Members of the research team played roles such as Bridge Officer on Watch (OOW) and Fire Teams 1 and 2. The interaction was described on roll cards and were based on observed activities from real fire drills. It takes 23 minnutes to complete the scenario.

(4) **Debriefing:** After the drill, each participant underwent a debriefing session lasting approximately one hour. During this session, they used the retrospective think-aloud method to watch and comment on recorded test sessions. Participants provided feedback on specific events during the drill and the conceptual design of the DFC.

(5) **User Rating** Ratings of the DFC should be provided. After the debriefing, participants received a link to an online questionnaire. The questionnaire comprised eight usability ratings on a 7-point Likert scale, along with four open-ended questions regarding the effectiveness of the DFC and any obstacles to its use. Participants were encouraged to complete the questionnaire (Tab. 2) after reflecting on their demonstration experience.

3.3.3 Data Collection. The study gathered different types of data, such as feedback from the familiarization phase, video and audio recordings from the simulation-based user testing, eye-tracking data, transcriptions of the debriefing interviews, and responses from the rating of the DFC. All data is securely stored on an encrypted server managed according to a data management plan. This publication includes data from the debriefing and the user ratings as described in section 3.3.2.

3.3.4 Data Analysis. The analysis involved viewing the debriefing recordings to identify and note themes related to usability of the DFC.

4 DFC INTERFACE

The first concept of the DFC was described by Kaland [9] and in the further progress of this project expert reviewed and improved in iterative steps. The interface of the digital fire central comprises five primary areas, as illustrated in Fig 3. The central component is the Deck-plan of the ship, drawing inspiration from traditional paper fire safety plans and encompassing all pertinent elements. Beneath the deck plan, panels display sensor readings from various sections on the deck (Fig. 7). Additionally, the interface incorporates a timeline (Fig. 11), an emergency control panel (Fig. 11), an option to toggle between displaying and concealing specific information (Fig. 17), and finally, a menu bar (Fig. 18) located at the bottom of the interface. A detailed description of each of these elements follows in the subsequent subsections.

4.1 The Deck Plan

The digital fire central interface consists of five primary areas, as shown in Fig. 3. The main component is the ship's deck plan (Fig. 4), which draws inspiration from traditional paper fire safety plans and includes all relevant elements. The Deck plan serves as a familiar tool for fire chiefs on ships, who traditionally utilize a paper version of this illustration. The Digital Fire Central (DFC) interface enhances the information provided by this emergency plan by offering additional details. Users can switch between different decks using the menu described in Section 4.5. Additionally, they have the option to transition to a 3D view (Fig. 5) to observe the fire's location in relation to other decks and identify the specific section affected.

Figure 4: Components included on the deck plan

4.1.1 Fire-Fighting apparatus. Users are provided with general information about fire equipment, including the placement of firefighting apparatus such as fire extinguishers, hoses, and hydrants,

Table 2: Items of the User Rating questionnaire [14]

Usability Ratings	Text Response questions
1. The DFC is easy to use.	1. What would be the most important differences between using the DFC, compared to how you work today?
2. The features meet my needs.	2. What do you see as the main benefit of the DFC?
3. The DFC provided a clear overview of the location of fire.	3. Do you see any possible barriers to the DFC concept? (Technical, organisational, work process, risks etc.).
4. The DFC provided a clear overview of the firefighting activities.	4. Was there anything missing: features/information which you would expect, or wish for?
5. The DFC provided a clear overview of how the fire was developing	
6. Using the DFC could support my job performance.	
7. Using the DFC could make it easier to do my job.	
8. The DFC could be useful in my job	

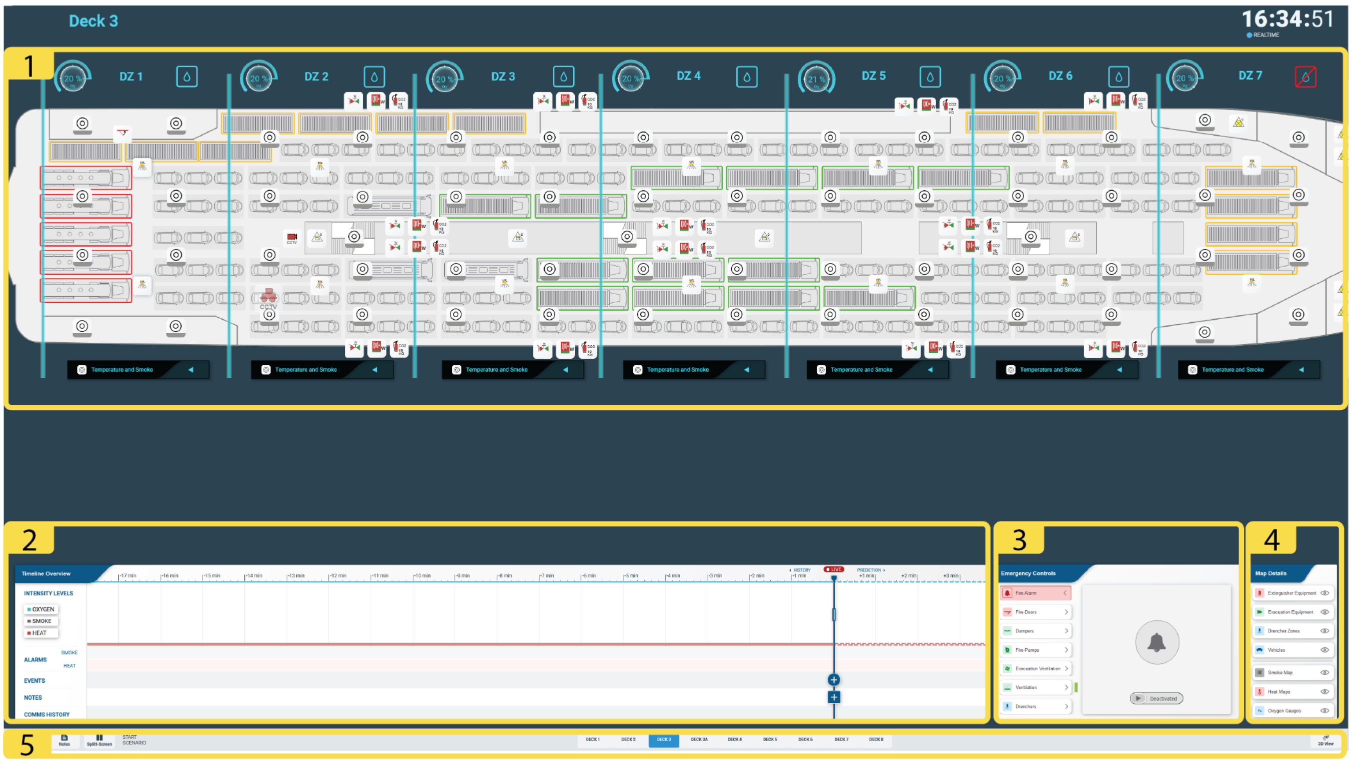

Figure 3: The illustrations shows the primary areas of the DFC, (1) the deck plan, (2) the timeline, (3) the emergency control panel, (4) the map details panel and (5) the menu bar.

which mirrors the details found in paper plans. The DFC provides further specifications, such as hydrant pressure and capacity, along with the date of its last periodic inspection (Fig. 6). Additional equipment, such as dampers, ventilation systems, and fire doors, is also displayed. To comply with regulations and aid user understanding, it is recommended to use icons and symbols as specified by the International Maritime Organization (IMO) [8].In this case, different detectors are used to detect fires, with combined heat and smoke detectors shown at their corresponding locations on the deck. If a detector does not detect any activity, the icon will appear in grey to avoid cluttering the interface with irrelevant information. The interface presents significant changes in temperature or smoke particle detection in three different formats, which are described in Section 4.1.2, 4.1.3, 4.2.

4.1.2 Detector Value Panel. Users can access all sensor readings from smoke and heat detectors positioned throughout the deck within the drop-down panel (Fig. 7). Even if a sensor is not situated on the main deck area, it is differentiated within the panel. For example, staircases, machine rooms, or isolated storage areas are highlighted in grey shading, aiding users in associating information with the correct sensor. The approach simplifies the display of sensor data by not showing temperature and smoke readings on the emergency plan interface, reducing clutter.

4.1.3 Smoke and Heat map. The second visualization (Fig. 8) uses overlays of different patterns to show how heat and smoke spread on the deck, using data from sensors. There are three different visualization states based on smoke and heat values (Table 3). Stage 1 shows values between 10-39% smoke density, Stage 2 shows values between 40-79% smoke density, and Stage 3 shows values exceeding

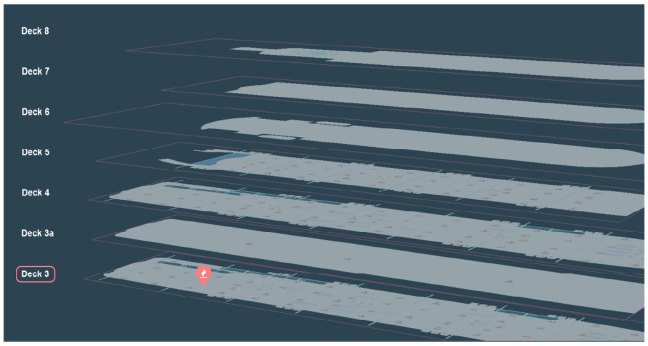

Figure 5: 3D map of the decks to show the location of the fire in relation to the other decks

Figure 6: Three types of fire-fighting apparatus (a) Hydrant with additional information about pressure, capacity and last periodical test, (b) Fire Extinguisher with additional information about weight, Type and Last periodical Check (c) Fire hose, with additional information about length, parameters and last periodical test; all additional information are visible on press of the icon

80% smoke density. Heat values are classified as Stage 1 (43-99 Celsius), Stage 2 (100-499 Celsius), and Stage 3 (over 500 Celsius). The stages on the map are separated by solid black lines, as shown in Fig. 8. Users can enhance detail visibility by toggling the visibility of these maps on and off via the Filter panel.

Table 3: Different Stages of Smoke and Heat visualisation. [14]

Categorie	Stage 1	Stage 2	Stage 3
Smoke Values [%]	10-39	40-79	>80
Heat Values [°C]	43-99	100-499	>500

4.1.4 Oxygen Gaugs. Oxygen plays a crucial role in combustion and the sustenance of life on board. Thus, the oxygen sensor information from various deck sections is displayed above each drencher zone. Drencher zones, which are based on overhead water drenchers, are typically separated into different sectors. Oxygen levels across sectors help the fire chief make decisions, such as when to close dampers and shut down ventilation to reduce combustion support factors or when to activate high-pressure ventilation to maintain smoke-free evacuation routes. Oxygen gauges show three levels:

(1) **Blue Zone:** The oxygen levels required for human respiration and combustion fall between 19.5% and 23.5%.
(2) **Orange Zone:** which has oxygen levels between 17% and 19.5 7%, can potentially induce hypoxia in humans but still sustain persistent combustion.
(3) **Red Zone:** which has oxygen levels below 16%, poses a challenge to human survival and hinders flame persistence.

4.1.5 Stowage Cards. Along with oxygen, heat and "fuel" are essential components of fire, so it is important to be aware of the quantities and locations of combustible materials on deck. It is also crucial to know the quantity and location of vehicles, especially electric vehicles, and the presence of hazardous goods. This information is presented through storage cards (Fig. 9), which come in various versions that distinguish between following units:

- Personal vehicles (such as cars, electric vehicles, and buses).
- Cargo types are classified based on:
  - Presence of towing vehicles
  - Container loading capabilities
  - containment of liquids, powders, or pellets within silo/tank trucks.

Stowage cards encompass the following details:

- Trailer identifier for clear identification.
- Booking number for internal reference.
- Volume estimation of combustible material.
- Details indicating cargo category.
- Fire hazard rating, distinguishing between low, medium, and high risks.
- UN or ADR pictograms, if applicable, providing quick hazardous cargo identification.
- Additional information accessible via the arrow icon, including cargo documents and thermal (FLIR) imagery.

4.1.6 Drencher Zones. Drencher zones, encompassing strings of drenchers, are segregated into sectors that can be individually controlled. Some sections may be structurally separated, while others remain open. Each drencher zone features a unique label displayed above the sector, aiding in guiding fire teams across the deck. Additionally, a symbol next to the label indicates whether the area can be extinguished with water or if contact with cargo should be avoided.

4.2 Timeline

The timeline (Fig. 11) is a tool for operators and external parties, aiding in maintaining situational awareness throughout the firefighting process. Its usefulness extends beyond immediate firefighting operations, including training purposes and debriefing following a fire incident. The timeline comprises several components, which are described below from bottom to top:

(1) **Communication History:** This section archives all communications with the various roles involved in the firefighting process as audio snippets. It enables all involved parties to revisit specific voice segments as needed.

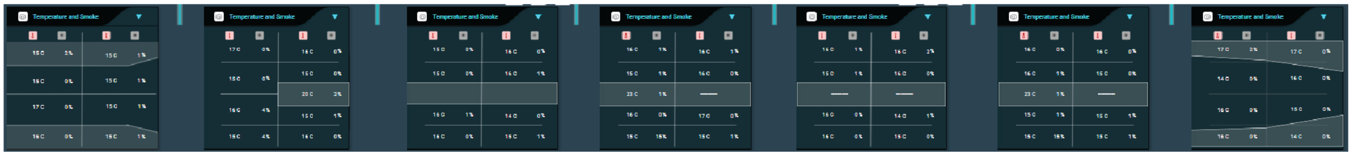

Figure 7: The detector value panel shows the sensor readings of each combined smoke and heat sensor on deck in the relation of his position on deck.

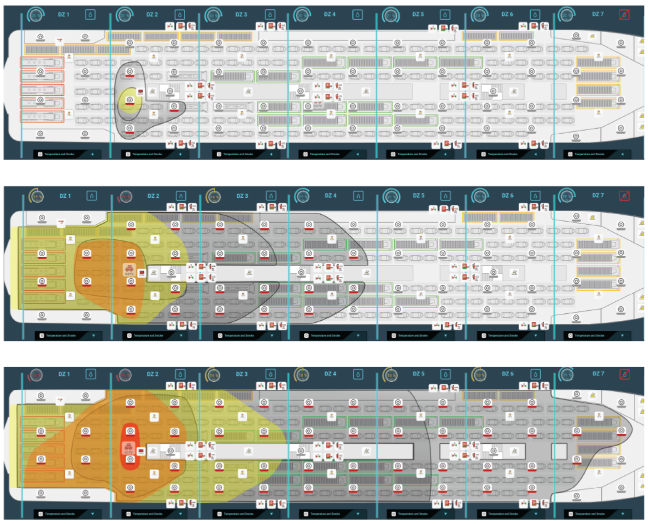

Figure 8: (Top) Smoke and Heat-map in the Beginning of an Fire Incident; (Middle) Smoke and Heat-map after the fire and smoke are spreading on deck; (Bottom) Smoke is covering the complete deck and fire has occupied larger areas of the deck, drenchers in zone 1 to 3 are activated

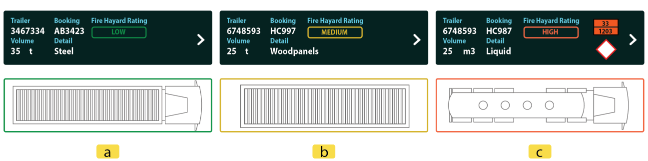

Figure 9: (a) Vehicle/cargo with low fire hazard; (b) Vehicle/cargo with medium fire hazard; (c)Vehicle/cargo with high fire hazard;

(2) **Note Section:** The note section allows for the addition of general information or notes to the timeline, serving as a diary for later debriefing purposes.
(3) **Event Section:** The event section includes two types of events. Events can be automatically generated based on actions taken by the operator, such as engaging with tasks in the emergency panel (Section 4.3). Other events are manually inputted, documenting instances such as when the fire team was ready or when boundary cooling was initiated.
(4) **Alarm section:** The alarm section is divided into two parts for smoke and heat detection. A marker is placed on the timeline when a detector is activated, providing an overview of the incident's extent based on the number of activated detectors.
(5) **Intensity level:**Intensity level: The section on intensity levels presents a graphical representation of heat, smoke, and oxygen intensity levels on the selected deck. Users can observe how these parameters fluctuate during the incident. In addition, predictions are made to estimate how fire suppression activities may affect the incident's progression, shown by dashed lines.
(6) **Time index:** Located at the top, the time index displays a historic timeline that expands as the fire incident progresses and a future timeline indicating predicted areas. The time slider (Fig. 10) allows users to navigate backward in time to observe the fire's development or review smoke and heat map data and measurements. Visualizations are displayed on a separate card. By clicking on 'live,' users can return to the present view.

This timeline is useful for managing ongoing firefighting operations and for training and post-incident analysis. It can enhance the overall effectiveness of hazard control on large RoRo ships.

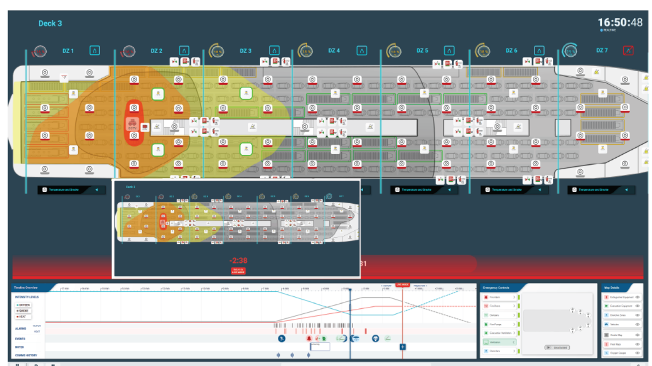

Figure 10: Timeline slider to see the development of the fire over time

4.3 Emergency Control Panel

The emergency control panel incorporates several functions that are typically located in different places on the bridge or completely separate areas of the vessel. This requires extensive communication between the various roles on board. The panel consists of 7 control elements, strategically arranged to guide users in taking timely countermeasures to manage the fire. A green status LED accompanies each task, acting as a checklist indicator. To prevent

Figure 11: The timeline showing a some parts of a fire incidents with elements described in section 4.2

accidental activation or deactivation, users must hold and slide a slider for these actions, with the system providing visual feedback on successful execution.

The following emergency controls are explained in more detail:

- **Fire Alarm:** This control allows the user to activate or deactivate the ship's general fire alarm following a specified procedure (Fig. 12).
- **Fire doors:** Fire doors protect different areas of the vessel, with different classifications (A and B) indicating their fire resistance duration. Users can either close all doors simultaneously or select specific doors. The status of the doors changes from grey to green bars upon successful closure.
- **Dampers:** Fire dampers installed in ventilation ducts prevent the spread of smoke or fire through the ventilation system. Users can remotely open or close dampers for entire decks or specific sections and receive visual feedback on the damper status (Fig. 13).
- **Fire pumps:**These pumps provide the water required for firefighting, drawing from onboard freshwater tanks or, if necessary, from nearby water sources. Users can activate valves and pumps from the panel, with highlighted green valves indicating open and running pumps signalled by a play icon and turbine animation (Fig. 14.
- **Evacuation ventilation:** To keep certain routes clear of smoke for safe evacuation, users can activate evacuation fans to create positive pressure conditions. Inactive fans are indicated by grey icons, while active fans are indicated by green play icons and rotating animations.
- **Ventilation:** In addition to evacuation ventilation, normal deck ventilation provides fresh oxygen to support combustion. Operators can control the ventilation, including stopping it to reduce the oxygen supply, or starting it in certain areas to clear smoke for improved visibility, with visual feedback mirroring that of the evacuation ventilation (Fig. 15.
- **Drencher:**Overhead drencher systems disperse large volumes of water to targeted zones, typically where the fire is located. Users can select zones for the drencher application, with panel feedback indicating zones unsuitable for water extinguishing. Limitations on zone selection and operational progress are visually communicated, allowing users to manage drencher activation accordingly. In addition, users can stop the drencher operation via the panel interface (Fig. 13).

This emergency control panel streamlines firefighting procedures, with the goal to improving response efficiency and safety measures aboard large ro-ro vessels.

4.4 Map Details Panel

The Digital Fire Central (DFC) interface presents operators with all the information they need, which can sometimes be overwhelming. To overcome this, users can hide certain elements to focus on specific details as required. The panel shown in Fig. 17 allows the user to control various map details, including.

(1) **Firefighting equipment:**Users can toggle the display of firefighting equipment on and off to reduce map clutter.
(2) **Evacuation Equipment:** This feature allows users to toggle the display of evacuation equipment.
(3) **Extinguisher Zones:** Users can choose to show or hide drencher zone separators and labels to make the map less cluttered.
(4) **Vehicles:** Users have the option to show or hide vehicles, affecting only normal cars, electric vehicles and cargo vehicles that affect combustion. Higher-risk vehicles, detectors and drencher positions cannot be hidden.
(5) **Smoke map:** Enabling or disabling the smoke map gives users a better understanding of how heat spreads.
(6) **Heat Map:** Similarly, users can disable the heat map to gain a clearer view of factors such as smoke distribution.
(7) **Oxygen gauges:** Users can choose to show or hide oxygen meters on the map.

Certain details such as detectors, vehicles and high-risk cargo drencher positions can not be dissabled by the user. Map details only affect the deck plan shown in Fig. 3 (1) and Fig. 4. These customization options allow operators to tailor the interface to their specific needs, enhancing the usability and efficiency of managing fire hazards onboard large ro-ro vessels.

4.5 Menu Bar

The menu bar gives the user access to the general functions of the Digital Fire Central (DFC). The following items are available in Fig. 18(1):

- **Start menu:** Allows the user to initiate actions such as restarting, shutting down or updating the DFC.
- **Notes:** This option provides access to the notes section where users can read existing notes and add new ones. During a fire event, notes are automatically timestamped and placed on the timeline for reference.
- **Split screen:** Users can switch between full-screen and split-screen views. This feature allows them to either view the deck plan in full-screen mode or have the 3D view (Fig. 5) on the second half of the screen for enhanced visualization.

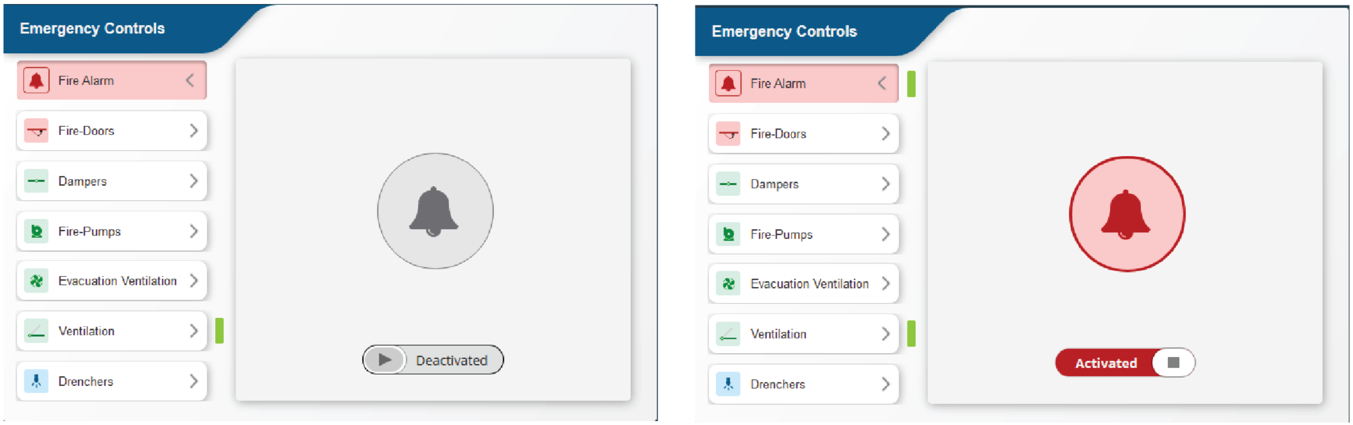

Figure 12: Switch panel to stop or avtivate the fire bells.

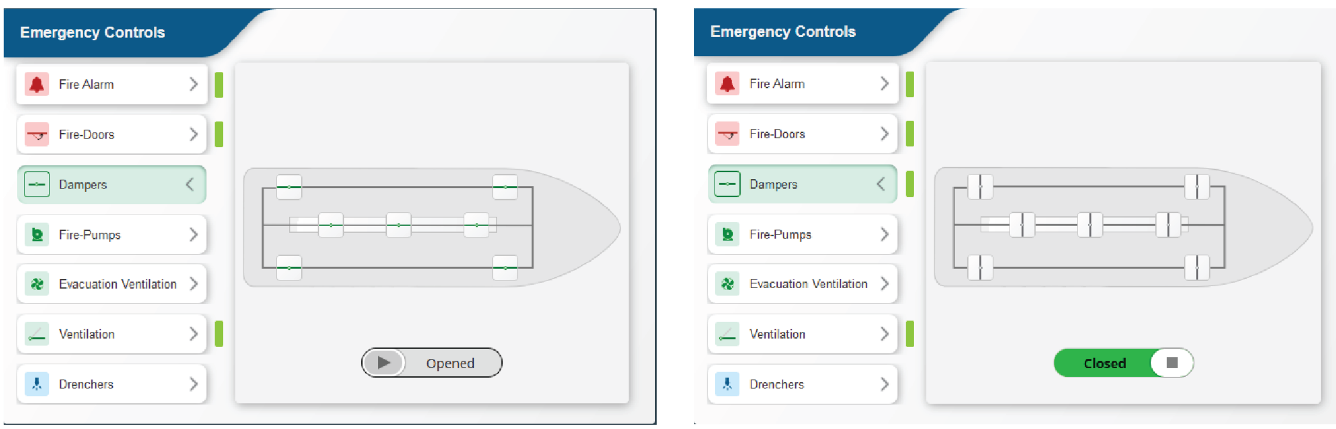

Figure 13: Switch panel to open or close dampers on the selected deck the left figure shows all dampers on the deck are opened, on the right illustrations the dampers are all closed.

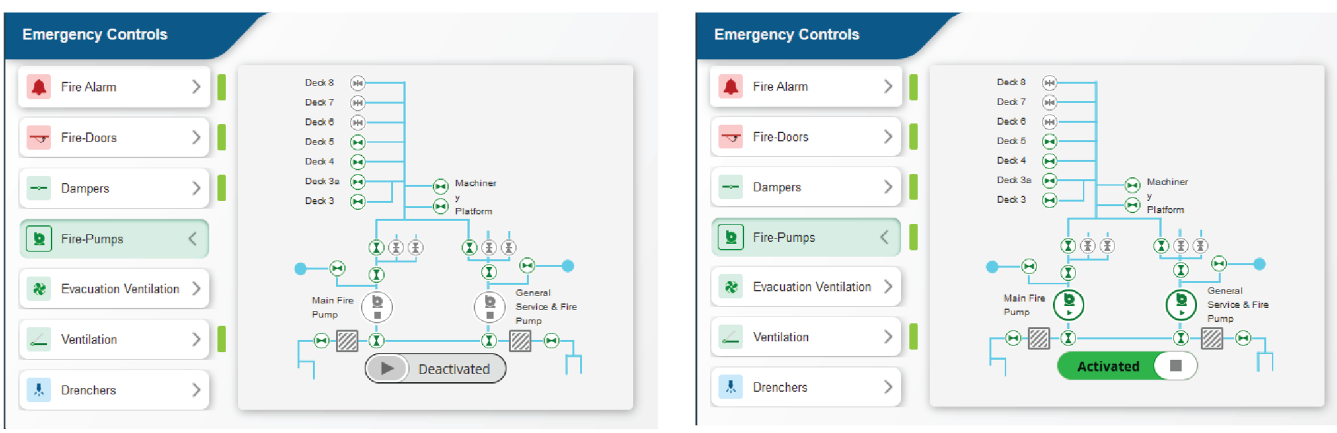

Figure 14: Switch panel to control the fire pumps and valves, in the left figure the fire pumps are inactive some valves are open, the right illustration shows active fire pumps.

Fig. 18 (2) allows users to navigate between different decks and view information specific to each deck.

Fig. 18 (3) allows the user to toggle the visibility of the 3D view in full-screen mode.

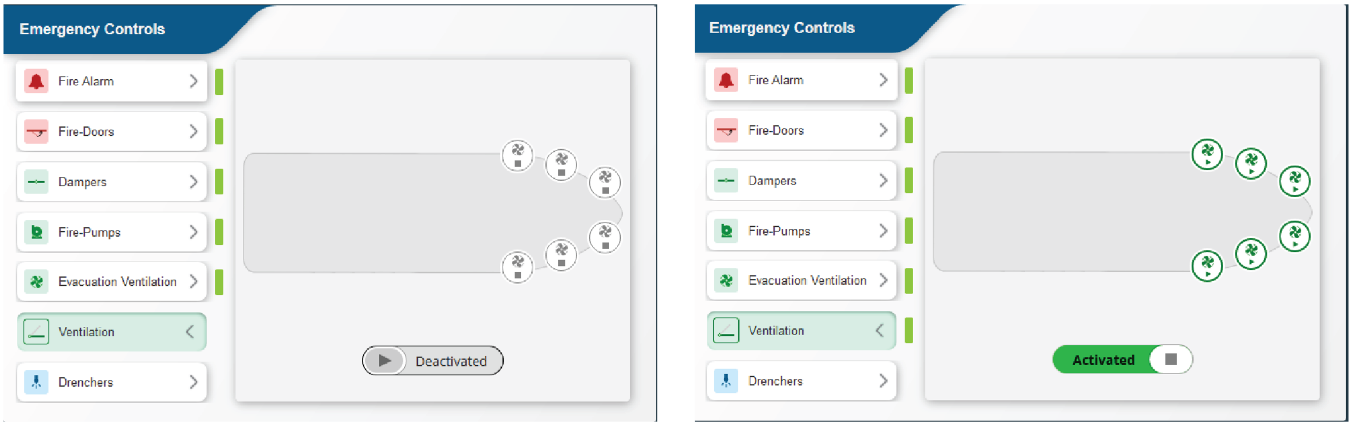

Figure 15: Switch panel to control the ventilation, the left figure shows inactive ventilation, the right figure shows the active ventilation.

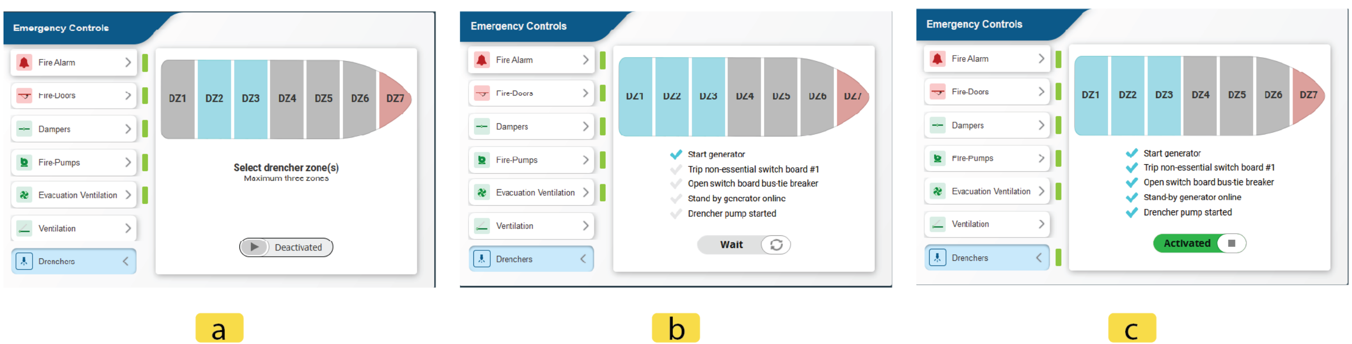

Figure 16: Switch panel to control the drenchers. (a) drenchers are deactivated, drencher zone 1 and 2 are preselected as a recommendation, zone 7 should not be drenched.; (b) operator select an additional drencher zone based on evaluating the situation and uses the maximum capable drenchers. The operator started the activation, now the system is running the startup procedure; (c) The startup procedure was successful and the selected drenchers are running.

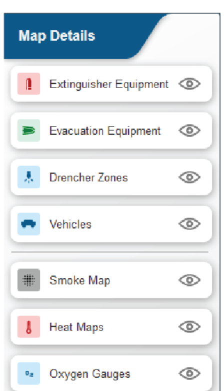

Figure 17: Panel to toggle between show or hide elements on the deck plan.

All interactive elements are strategically placed in the lower part of the screen to facilitate controlled operation, utilizing the hand rest and railing of the physical DFC. This design ensures that users can effectively interact with the interface even in rough sea conditions, maintaining operational efficiency and safety on board.

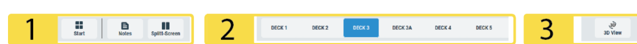

Figure 18: Menu bar for functions to (1) Open the Start Menu, Open Notepad, and toggle between split-screen and normal view; (2) Tab to switch between different decks; (3) open the 3D view as a full sized view.

5 RESULTS

The 23-minute simulation experiment was successful for all participants. Every participant tackled the fire extinguishment task in their own unique way. One participant quickly activated the drenchers in the three specified zones upon detecting heat. Subsequently, smoke divers were dispatched when the DFC panel indicated the fire was extinguished to investigate the area of incidents. Despite attempting to deactivate one of the drenchers to avoid wetting the fire team, the programmed scenario prevented this action. However, the participants were successful in shutting down the drenchers once no smoke or heat remained. In contrast, one participant activated the drenchers later in the process but still succeeded in the scenario, while another opted to activate the drencher in only one zone, with the aim of cooling down the section containing hazardous cargo closest to the fire, rather than immediately targeting the source of the fire with the drenchers. User feedback regarding the DFC was generally positive, although some expected features were noted as missing. It's essential to emphasize that the results offer an initial evaluation rather than an in-depth qualitative analysis. The following sections present the study results across four primary domains. Firstly, feedback on specific visual elements of the DFC is provided. Secondly, feedback is discussed within the broader context of the DFC, incorporating perspectives on organizational structures. Thirdly, the user rating questionnaire results are presented. Finally, an analysis of the DFC's effectiveness, efficiency, and user satisfaction is outlined.

5.1 Feedback on Interface Elements

The subsequent section examines how users perceived the individual UI elements and features within the DFC.

5.1.1 The Deck Plan. The users demonstrated a clear and accurate understanding of the ship's arrangement and overall display layout presented in Section 4.1, seamlessly navigating between functional areas. They adeptly interpreted the data from the heat and smoke sensors, including the supplementary information provided in drop-down boxes, accurately correlating sensor placements with the ship's layout and deciphering numerical data. The icons' layout, symbol choice, and fire plan received high praise for facilitating an easy understanding of the ship's layout, emergency equipment, and cargo positioning. Participants were able to maintain awareness of their deck location and the fire's location throughout. However, the prototype's plans had some information gaps, such as missing frame numbers, manual call buttons, and emergency door indicators. These gaps hindered participants' ability to provide specific instructions to firefighters. Furthermore, the absence of a marker to track the fire teams' positions further impeded user effectiveness

5.1.2 3D Map. One participant expressed inefficiency in having to switch between different decks to gain an overview. They suggested the inclusion of small deck pictures with corresponding numbers for direct access. This would eliminate the need for frequent deck switching. The 3D view was not used that frequent but having this as a mini map in the corner of the deck plan would be helpful to get a better perspective awareness.

5.1.3 Fire-Fighting Apparatus. The use of IMO symbols in the iconography was generally understandable without explanation. However, participants expected the icons to function as buttons and attempted to click on them multiple times, indicating a need for consistency in interactive elements. Although familiar symbols were comprehensible, participants found the lack of clear interaction cues confusing. Furthermore, participants observed that information about emergency equipment, such as pressure readings on fire hoses or hydrants, would be more relevant for firefighting purposes than the last service date of the system.

5.1.4 Detector Value Panel. Every participant understood the relationship between sensor placements and the information provided in the drop-down menu, as well as the numerical data itself. Nevertheless, they expressed a preference for having the values directly displayed next to each sensor symbol instead of within a drop-down menu. Additionally, one participant proposed the option to toggle temperature indicators for individual sensors, offering users increased flexibility. Another participant highlighted the importance of a simplified map view, without the need to read detector values, emphasising the value of the heat-layer feature.

5.1.5 Smoke and Heat Map. The dynamic nature of the ship's fire plan was widely commended for its practicality. Participants particularly appreciated its ability to quickly identify fire locations and understand the overall situation at a glance, which contrasted favourably with traditional methods relying on verbal directions and static fire plans. This capability was considered essential in significantly expediting response times. No changes in content have been made. The use of a colour scale to indicate temperature during high cognitive load was preferred over a table of values as it facilitated rapid assessment. However, participants identified the absence of a legend to interpret temperature colours as a limitation, leading to instances where normal temperatures were overlooked. Right now, when many smoke detectors go off, they just tell the operators smoke is spreading. But the DFC goes further, showing how the smoke spreads and which way the fire is developing. One participant pointed out, that this would help the captain see the big picture, like figuring out where to approach the fire, even if lots of detectors are alarming.

5.1.6 Oxygen Gauges. All participants recognised the importance of oxygen gauges and understood their indications. However, their primary use was seen as assessing the breathability of the air for firefighters rather than assessing the asphyxiation potential of the fire. One participant specifically emphasised that they wouldn't rely on oxygen gauges during a fire as firefighters on deck would be equipped with breathing apparatus and would prioritise rapid extinguishing over waiting for asphyxiation.

5.1.7 Stowage Cards. Most participants agreed that the cargo information was crucial. While the color-coding on the stowage cards wasn't initially clear, it became very helpful once it was explained. Participants expressed familiarity with the IMDG code for dangerous goods and suggested that it should be included on the stowage cards. hey also suggested that the cargo's water extinguishing suitability should be clearly indicated on the cargo itself and not just in the drencher zone. In particular, participants highlighted how this presentation of cargo information could significantly improve the efficiency and effectiveness of crew coordination during firefighting operations.

5.1.8 Timeline. The timeline (Fig. 11) emerged as a highly valued feature of the system from the outset. One participant articulated its usefulness by noting: "I can see when it started and I guess the alarm will show up here [points to alarm plot]. If I come in and I am new to the situation, I would see that there was an alarm 11 minutes ago". Participants found the historical plot very useful and easy to follow. It helped them quickly grasp what was happening at the scene, including the alarms triggered and the changes in heat, smoke, and oxygen levels on deck. The graphs provided valuable insight into the effectiveness of the firefighting efforts.

Event markers were mentioned as a valuable tool for highlighting critical events. Participants appreciated their integration with the historical overview, as they facilitated a clear understanding of the actions taken. While the logging process was intuitive, with participants expecting actions to be logged even before emergency operations were activated, only one participant manually added an event marker. In interviews, everyone admitted they forgot about the menu and wanted the event icons always visible because they were crucial. In addition, the unlabelled plus symbol used to access the menu was perceived as one element with the labelled 'Events' row.

Participants expressed uncertainty about predictions. Although they understood the concept, two participants preferred to rely on smoke diver reports over automated predictions due to unfamiliarity with the calculation process. They were reluctant to rely solely on a graphs for decisions. However, one participant heavily relied on predictions to evaluate the effectiveness of actions taken. However, one participant used the predictions extensively to assess the effectiveness of actions taken.

The slider feature (Fig. 10) was seen as a valuable addition, allowing visual comparison of fire development by scrolling back through the timeline. However, no participant used this feature during the scenario.

Despite understanding the note function, participants did not find it necessary during the scenario, preferring the ease and naturalness of jotting quick notes on paper. In addition, one participant commented that the notepad obscured a significant portion of the screen. However, despite the immediate appreciation of the timeline, two participants anticipated the inclusion of a drawing function in the notepad.

5.1.9 Emergency Control Panel. The design of the emergency control panel was universally praised for its ease of use and intuitive layout. Each participant navigated quickly and without hesitation through the various controls, demonstrating the effectiveness of the design. The location of the panel was found to be appropriate, with all participants finding it quickly and without difficulty. However, participants expressed a desire for immediate visual feedback on the map for initial actions such as closing fire doors, deactivating ventilation and activating fire pumps.

At first, participants didn't immediately grasp that the activation switch was a slider. While all participants initially tried to push the slider, they quickly adapted to the sliding motion. During both the training session and the actual scenario, no participant attempted to use it as a button again.

There was a misunderstanding by one participant regarding the 'fire alarm' button, interpreting it as muting the entire alarm system rather than activating/deactivating the fire alarm itself.

Even with some small confusions, everyone managed to start the fire pumps and drenchers. Although they got how to start the fire pumps, they missed the pressure indication on the pumos or the drenchers. One person chose to only use the drenchers in one zone because there was dangerous cargo nearby, aiming to keep the fire from spreading. However, they expressed uncertainty about not using the drencher zone directly above the fire due to lack of visibility. Nevertheless, all participants operated the drenchers correctly and understood the implications of their actions.

The indication of an inaccessible drencher zone (DZ7) was easily understood, although participants found the reason for its inaccessibility (dangerous cargo) unclear.

The participants quickly grasped both the evacuation ventilation and deck ventilation controls, correctly using them during the scenario. Overall, they were mostly satisfied with how the emergency controls functioned, finding them easy to access and operate. However, they also noted that having multiple tasks to handle created a lack of checks: "Usually, you just say things on the radio and it is started by the bridge team for instance (i.e., pumps), but here I have to do it myself. 'Did I actually do it?' It is an additional burden." [14]

Participants also suggested improvements to the green indicator LEDs on the control panel, noting a discrepancy between the status displayed and the action taken. They expected more comprehensive indications on the map to match their actions.

5.1.10 Map Details Panel. None of the participants used the toggle buttons for the different layers during the scenario. However, all participants demonstrated a clear understanding of the functions and how to use them correctly and without error during the familiarisation phase. Whilst the option to remove information using the menu bar was not used during the scenario, it is conceivable that this functionality may become necessary in more complex scenarios.

5.2 Context of Roles

The design of the Digital Fire Centre (DFC) was predominantly perceived as most beneficial to the bridge, serving as a tool for the master and assistant officer, according to the participants' feedback. While all of the participants in the study typically serve as fire officers on their vessels, the test scenario revealed differences in firefighting organisation between the ferry operators, particularly concerning the role of the fire officer. On one vessel the fire chief is primarily located on the bridge, in contrast to other organisational structures where they are being close to a fire and operating from the nearest fire central. The participants emphasised the importance of sensory perceptions and real-time observations in firefighting scenarios, as opposed to relying solely on screen-based information. Communication dynamics were also noted, with participants accustomed to managing multiple communication channels during emergencies. – " I have 3 ears and listen to 3 radio conversations simultaneously". While there was consensus on the usefulness of the DFC for directing firefighting operations from the bridge, questions were raised about its potential impact on the organisation of firefighting operations. Participants considered how the DFC would accommodate tasks traditionally performed by different individuals, such as communication and equipment activation. Barriers and risks associated with the DFC were discussed, including concerns about technology dependency and usability in adverse weather conditions. Participants also raised issues around decision-making autonomy, cautioning against over-reliance on automated systems without human oversight. Certain features of the DFC were conceptually appreciated, but participants expressed reservations about relying on information they didn't fully understand. Participants were also sceptic towards the accuracy and interpretation of data provided by the DFC, highlighting the importance of maintaining human judgement and scepticism alongside technological advances.

5.3 Questionnaire Result

Participants agreed that the DFC was easy to use and provided a clear overview of the fire (Fig. 19) - P2: *"It is like the digital representation of materials we use today but just everything in one place"*; P3: *"Much better overview of the situations and much easier to do a proper evaluation of the fire situation"*However, there was less consensus on whether the features fully met their needs, probably due to their usual role as fire managers rather than bridge operators as in the test scenario. User mentioned there should be a more salient representation of important structures like fire doors dampers and emergency exits, Stair cases, these should be provided with more information when they are clicked. A considerable deficit was the missing frame numbers which divides a deck in multiple small sections, which is important to guide and navigate fire fighters on the decks, same applies for the numbering of the staircase entries and detectors are not numbered in the interface. Users also expect clear feedback on actions e.g. fire doors open, fire doors closing, fire door closed. The fire pumps indicate that they are running, for the users it would be helpful to have pressure readings as an additional information. The main benefits of the DFC reported by the participants pointing out the easy way to assess the fire and control the fire equipment. - P2 *"The developement of the fire "*; P3 *"Creating an overview of the location and development of the fire."*; P4 **"The good overview and that you have an easy access to all the different fire controlls"**.

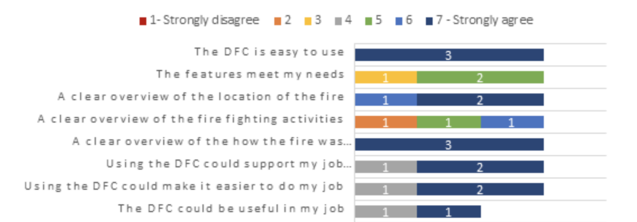

Figure 19: User response on the questionnaire shown in Table 2 [14].

A big missing functionality is to place markers on the map, where fire teams are located on the map, even better would be if the fire fighters would wear beacons and could automatically be displayed on the map. Currently they place colored dots on paper maps to track were the fire teams are. Participants identified the key contribution of the DFC as its ability to visually represent the location and progress of the fire, consolidating data and controls into a single interface. This centralised approach was seen as an advantage over using multiple tools.

6 DISCUSSION

Overall, the Digital Fire Central (DFC) proved effective for its intended purpose to improve fire fighting abilities, with users understanding the deck plan and finding the timeline tool useful for situational awareness. However, some participants emphasised the importance of physical proximity to the fire for full sensory input. They suggested a tablet application with reduced views, focusing on visual elements such as smoke and heat maps, as a valuable addition to future fire centres.

The centralisation of emergency tools on one panel was praised, although some details such as pump pressure and fire door status were missed. Participants preferred not to hide map elements for fear of oversight, and found the system manageable with its current information load. Surprisingly, users felt able to oversee tasks typically performed by multiple roles without feeling overwhelmed, suggesting potential for remote fire management and the support of reduced manning on ships, at least for managing the fire.

The use of pictorial elements and minimal text was praised for overcoming language barriers. However, limitations included the constraints of the scenario and the small number of participants, with some features such as the 3D map and note-taking functionality not directly explored. Nevertheless, feedback was received on these aspects.

6.1 Study Limitations

Although the DFC was evaluated with only three participants in the main study and additional participants during the design process, and has only questionnaire answers from these three, this study provides valuable insights into its design and functionality. While a larger sample size is benefitial for user testing it always depends on the stage of the usability cycle [15]. Turner [15] also points out that even small groups can provide valuable feedback. This could be especially a point in specialised fields such as marine safety where recruiting experienced professionals can be challenging.

Our participants, all fire chiefs with extensive experience (Tab. 1), provided important insights into the practical application of the DFC and potential improvements. To increase the robustness and generalisability of the study, future research should include more participants from different roles within the hazard control community. In addition, while this study focused on the cargo areas of ro-ro vessels, future research should also include passenger and accommodation areas.

By acknowledging these limitations and outlining a clear path for future research, this study contributes to the development and refinement of advanced fire management systems in the maritime industry.

7 CONCLUSION

In conclusion, the design and initial user evaluation of the DFC demonstrated its ability to centralise information and tools for fire risk management. Users adapted quickly, despite differences from their usual organisational structures. The study suggests the inclusion of additional functionality based on user feedback, highlighting the benefits of a user-centred design approach. Further analysis of the collected data, including insights from the eye tracker, and integration of actual sensor usage are suggested for future development. The research questions are just partly answered, in this publication. What could be seen is that the concept works good to get a good overview about the situation, this is especially helpful for roles on the bridge or in control rooms to have a big picture about the situation. For the role of the fire chief itself a smaller representation is more helpful, to take the fire central to the location of the incident to guide the fire team. The number of participants is to little to take a clear indication if the management of the fire is more efficiently with the fire central, this need to be investigated after implementing the fire central in real operation.

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