D5.3 Preliminary policy recommendations based upon the HS4U pilots and technologies

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DOCUMENT SHEET

PROJECT ACRONYM	HS4U
PROJECT FULL TITLE	Healthy Ship 4U
PROGRAMME	Horizon Europe
TOPIC	HORIZON-CL5-2021-D6-01-12
TYPE OF ACTION	HORIZON-Research and Innovation Actions
GRANT AGREEMENT	101069937
START DAY	1 September 2022
DURATION	36 months

DOCUMENT INFORMATION

DELIVERABLE NUMBER	D5.3
DELIVERABLE NAME	Preliminary policy recommendations based upon the HS4U pilots and technologies
LEAD BENEFICIARY	ABS
WP	5
RELATED TASKS	T5.3
TYPE	R – Document, report
REVIEWERS (ORGANISATION)	NTUA, HPI
DELIVERY DATE	31.08.2025
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DISSEMINATION LEVEL

PU	Public	X
PP	Restricted to other programme participants (including the EC)	
RE	Restricted to a group specified by the consortium (including the EC)	
CO	Confidential, only for members of the consortium (including the EC)	

DOCUMENT HISTORY

VERSION	DATE	CHANGES	REVIEWER / CONTRIBUTOR
0.1	08/07/2025	First draft	Yvonni Damianidou (ABS), Vassilis Zouzoulas (ABS)
0.2	10/07/2025	Input from ECOSENSE	Inbal Ierer (ECOS)
0.3	15/07/2025	Input from AETHON, RWO	Spyros Kolovos (AETHON), Kiriaki Kokona (RWO)
0.4	16/07/2025	StreamHandler-related pilot activities	Nasos Grigoropoulos (INTRA), Gerasimos Markantonatos (INTRA), Amalia Ntemou (INTRA)
0.5	17/07/2025	Input from CNTlab, UNP	Arturo Sommariva (CNTlab), Fabio Querido (UNP)
0.6	22/07/2025	Input from UTH	Dimitris Iakovidis (UTH)
0.7	23/07/2025	Input from HPI (Appendix 1)	Christina Golna (HPI)
0.8	04/08/2025	Input from ECOSENSE	Inbal Ierer (ECOS)
0.9	05/08/2025	Content review	Spyros Hirdaris (ABS)
0.10	19/08/2025	Various updates	Vassilis Zouzoulas (ABS), Yvonni Damianidou (ABS)
0.11	19/08/25	Content review	Marc Bonazountas (EPS)
0.12	22/08/25	Additional input from UNP, AETHON	Fabio Querido (UNP), Spyros Kolovos (AETHON)
0.13	24/08/25	Additional input from ECOSENSE	Inbal Ierer (ECOS)
0.14	27/08/25	Review by NTUA	Dimos Akouros (NTUA)
0.15	29/08/25	Additional input from UTH, Review by HPI	Dimitris Iakovidis (UTH), Christina Golna (HPI)
1.0	31/08/25	Final version	Vassilis Zouzoulas (ABS)

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ABBREVIATIONS

ABS	American Bureau of Shipping
BV	Bureau Veritas
CDC	Center for Disease Control and Prevention
CDF	Collaborative Digital Framework
DPO	Data Protection Officer
ECDC	European Centre for Disease Prevention and Control
EEA	European Economic Area
EMSA	European Maritime Safety Agency
EU	European Union
FFP	Fabrication, Falsification, Plagiarism
GDPR	General Data Protection Regulation
KPI	Key Performance Indicator
HS4U	Healthy Ship for You project
HVAC	Heating, Ventilation, and Air Conditioning
ICS	International Chamber of Shipping
IMO	International Maritime Organization
MCA	Maritime and Coastguard Agency
MDH	Maritime Declaration of Health
OMP	Outbreak Management Plan
PCR	Polymerase Chain Reaction
PEB	Project’s Ethics Board

PLF	Passenger Locator Form
PPE	Personal Protective Equipment
RA	Risk Assessment
RFID	Radio-Frequency Identification
SD	Social Distancing
SLR	Structured Literature Review
SMS	Safety Management Systems
SOPS	Standard Operating Procedures
SSC	Ship Sanitation Certificate
WHO	World Health Organization
WP	Work Package
WWED	Waste Water Epidemiological Device

Publishable Summary

Like land-based facilities, marine and offshore assets are vulnerable to outbreaks of infectious diseases. Such extreme events may significantly impact the health and well-being of seafarers and passengers, as well as severely disrupt normal maritime operations. Recent experiences from the COVID-19 pandemic demonstrated that managing a disease outbreak onboard cruise ships and large passenger vessels may be complex and unpredictable. This is the reason why an in-depth understanding of the epidemiological characteristics of a disease, a thorough appreciation of the societal and behavioural factors that impact passenger and crew adherence to guidelines, and availability of the details of a ship's infrastructure are today considered key indicators in predicting the progress of a health crisis onboard.

Traditionally the management of public health incidents and response activities is primarily the responsibility of a country's official authorities, as guided by the World Health Organization (WHO) and the International Health Regulations (IHR) authorities. The HS4U project reviewed the existing regulatory framework and published guidelines with the aim to identify content relevant to technical advice, measures, criteria, and parameters applicable to disease outbreaks occurring onboard ships.

Research demonstrated that while methods and protocols exist for disease detection and response, many remain vulnerable to human errors. This is because of their reliance on subjective judgment and ambiguous criteria. These errors can be influenced by several factors, including the training and experience of personnel, the cognitive load from processing large volumes of information, and the mental or emotional state of decision-makers. Access to medical screening and laboratory testing is not always guaranteed, potentially delaying the identification of infectious diseases and the timely activation of response protocols. The integration of technological tools for monitoring, controlling, and even predicting potential disease outbreaks on ships may help to significantly enhance the health and safety of passengers and crew.

This deliverable provides a summary of the HS4U project pilot activities, including:

- An overview of the technologies developed
- A summary of pilot activities conducted to test and validate technologies
- Key observations emerging from the analysis of experimental data and results
- Recommendations for updating existing shipboard protocols, policies, and equipment

The report is intended for use by the public. Technical deliverables and scientific publications that serve the interests of key academic or technical stakeholders are readily available on the project's website, https://hs4u.eu/.

1. INTRODUCTION

Over the past two decades, the emergence of several cases of communicable diseases whose spread reached global alert levels demonstrated the critical impact that international travel may have on global health. Notable examples include the H1N1 pandemic in 2009, which originated in Mexico [1], the Middle East Respiratory Syndrome Coronavirus, which was isolated in 2012 in Saudi Arabia [2], the Chikungunya virus, which emerged in the Americas in Saint Maarten in December 2013, the Ebola Virus in West Africa in March 2014 [3], [4], and the most recent Coronavirus Disease (COVID-19), which caused a global pandemic leading to disruption of the international trade and tourism.

Cruise ships, with their large number of passengers and crew, are particularly vulnerable to outbreaks of infectious diseases due to their semi-closed and often crowded environments. These effects may intensify because of regular social interactions that may take place on a cruise ship, group excursions, and the interaction of passengers and personnel during a trip.

According to Marshall et al. [5] who combined the reports published by Barbados Port Health Department from 2009 to 2013 communicable diseases appear in 15.7 cases per 100,000 passengers, with the most common being respiratory infections and waterborne infections. COVID [6], [7], [8].

The persistent threat of infectious diseases on cruise ships, highlighted by the COVID-19 pandemic, demonstrated the need to re-evaluate the current maritime health and safety regulations and protocols [9]. Additionally, it emphasized the importance of optimizing ship systems to better prevent, mitigate, and manage such health crises.

Various manuals and guides that set standards or suggest actions for managing or controlling communicable disease outbreaks on cruise ships have been issued by public health bodies. Tables 20 to 22, in Appendix 1, consolidate the available guidelines and recommendations regarding the management measures for the three most frequent infectious diseases (COVID-19, influenza, and gastrointestinal infections) as derived from a structured literature review carried out by [10]. Guidelines and recommendations may fall under three main pillars, namely prevention, screening and diagnosis, containment, and risk mitigation. They can be categorized as to when they are applicable, i.e., before embarkation, during travel, and prior to or during disembarkation.

The analysis demonstrated that prevention and risk mitigation measures are comprehensively addressed. Diagnostic procedures are also sufficiently detailed, with specific reference to the availability and accessibility of diagnostic tools and resources. However, despite the critical importance of screening and early detection measures, there is a noticeable lack of detailed guidance on tools and methodologies for conducting large-scale screening and early identification among passengers and crew onboard. The HS4U project was engaged to develop innovative solutions intended at addressing the issues outlined above, which are further elaborated in this report.

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2. THE REGULATORY FRAMEWORK

Maritime transport is critical to global trade and mobility. Yet, it poses specific public health challenges due to confined onboard living conditions and the international profile of passengers who frequently travel between ports. The emergence of infectious diseases such as COVID-19 emphasized the need to develop comprehensive regulatory frameworks and practical guidance on the prevention, detection, and management of virus outbreaks at sea. The review presented in the following sub-sections focuses on formal documentation related to public health protocols. Special emphasis is placed to guidelines addressing COVID-19 and gastrointestinal infections, which have been among the most prevalent health concerns in the cruise industry.

2.1 World Health Organization

The maritime industry is self-assured and operates under a regulatory framework established by the International Maritime Organization (IMO). Compliance is enforced through inspections conducted by flag states and verifications by port state control authorities. Any country whose ports or territorial waters are accessed by a vessel holds the authority to ensure adherence to international, national, and local regulations. Matters concerning health conditions onboard ships are regulated by the World Health Organization (WHO).

The first International Health Regulations (IHR) [11] were adopted by the World Health Organization (WHO) in 1969. They introduce universal requirements for the prevention and management of specific infectious diseases. The 2005 edition of this publication extends the scope of work to cover prevention, protection, and control, as well as the response of public health authorities, in ways that are proportionate to the potential consequences for public health and minimize interference with international traffic and trade. The WHO rules are legally binding for all of the participating member states (currently 194 countries). They outline obligations and formal procedures to be followed in situations that may involve public health risks with an impact on the international community.

The IHR provides the legal basis for other important health documents that may be applicable to international travel, transport, and sanitary protections. Examples are the Ship Sanitation Control Certificate (SSC), the Maritime Declaration of Health (MDH) and the Vaccination Certificates. According to the IHR, the competent authorities at ports are to be responsible for responding to events that could pose a risk to public health. This can be achieved by suitably choosing and implementing appropriate measures given as recommended options in the document. Possible hazardous events are identified through notifications by ships or other authorities during a ship inspection or even through informal routes.

In the maritime context, several key stakeholders are responsible for implementing and enforcing these obligations. Ship masters are tasked with monitoring the health status of those onboard and reporting any illness or unusual symptoms. Ship operators and owners must ensure that adequate policies and procedures are incorporated into their Safety Management Systems (SMS), in accordance with the International Safety Management (ISM) Code [12]. Flag States oversee compliance by vessels registered under their jurisdiction, while Port States and their corresponding health authorities conduct inspections, verify documentation, and may impose public health measures such as quarantine or disembarkation delays. Classification societies and industry associations support these efforts by providing technical standards, certification frameworks, and sector-specific guidance.

2.2 WHO Handbook for management of public health events on board ships

Although the International Health Regulations (IHR) assign responsibility to competent port authorities for managing public health risks on board ships, the decision-making processes, standards, and practices applied to date appear to vary significantly across countries.

To support the practical implementation of the IHR in maritime settings, WHO also published the Handbook for the Management of Public Health Events on Board Ships (2016) [13]. This document presents an operational guide that outlines a structured, risk-based approach for detecting and responding to public health threats on vessels, whether in port or at sea. The emphasis is on early detection, verification, risk assessment, implementation of control measures, and communication principles. It is useful for personnel working in public health, medical, veterinary, environmental, customs, port state control, and occupational health as well as shipping companies and ship crew. Although the document applies to a wide range of infectious diseases, existing guidelines are based on literary data and insights derived from previous large-scale health events, excluding the COVID-19 pandemic.

Currently, the implementation of public health management procedures onboard ships begins with an event detection, which can occur through routine surveillance, crew medical reports, or declaration of symptoms in the Maritime Declaration of Health (MDH) prior to port entry. Once an event is suspected, the next step is verification and risk assessment. This involves confirming the case (or cluster of cases), determine the nature of the illness, and assess their potential for transmission. Competent authorities, as defined by the International Health Regulations (IHR), are the designated national bodies responsible for applying public health measures. These may include port health services, ministries of health, or other specialized agencies. They are tasked with deciding on appropriate response actions, which may involve the isolation (quarantine) of affected individuals onboard or ashore, disinfection procedures, and, in extreme cases, denial of ship entry into port.

The handbook also describes measures to be implemented following clear indications of the presence of an infectious disease. These are built on 2 pillars, namely:

- measures with respect to persons (e.g., travel history, medical screening, vaccination screening, contact tracing, quarantine, isolation) and,
- measures with respect to ships and inanimate objects (e.g., ship inspections according to SSC, disinfection, vector control, and decontamination measures).

2.3 WHO Handbook for inspection of ships and issuance of ship sanitation certificates

The Ship Sanitation Certificate (SSC) is an internationally recognized document under the IHR that verifies a vessel's sanitary conditions. Infectious diseases on marine and offshore assets are transmitted through food, water, vectors (insects, rodents), air, direct contact, and indirectly, through contaminated surfaces. The WHO Handbook for Inspection of Ships [14] focuses mainly on managing risks related to vectors, contaminated food and water, and waste management.

The document is intended to be used as a reference manual for port health officers, ship operators, and other competent authorities in charge of implementing the IHR at ports and on ships. It outlines the administrative tasks and procedures required during inspections and offers a detailed guidance on various potential deficiencies and their solutions, that are categorized as applicable to the various ship areas.

2.4 Disease-Specific Protocols: COVID-19 and Norovirus

While the IHR and WHO handbooks provide the general frameworks for managing public health events, more specific guidance has been issued to respond to disease instigated emergency scenarios.

A few years ago, the COVID-19 pandemic prompted the publication of several operational guidelines by WHO, the International Chamber of Shipping (ICS), and other organizations. These disease-specific protocols illustrate how the IHR framework can be adapted to specific infectious agents and attempt to balance the need for public health protection against the need to ensure continuity of shipping operations.

For example, the WHO Operational Considerations for Managing COVID-19 Cases on Board Ships [15] presents a detailed response protocol that emphasizes the need for onboard screening, timely case identification, and safe isolation. The guidelines suggest that each passenger ship should develop a detailed management plan for handling disease outbreaks. Such a plan should specify isolation protocols for suspected cases, their clinical management, procedures for tracing potential contacts, and the modalities of further service (food, laundry, waste removal, etc.) to the isolated traveller. In addition, it outlines a set of measures related to disease prevention, such as cleanliness, social distancing, and pre-boarding screening. Last but not least it introduces the Passenger Locator Form (PLF) as an effective tool for traceability.

Norovirus, another highly contagious pathogen often associated with cruise ships, is subject to a unique set of control measures. This is because its biological properties allow it to resist many common disinfectants and persist on surfaces for extended periods. National guidelines, such as those proposed by the UK Health Security Agency and the U.S. Center for Disease Control and Prevention (CDC), recommend immediate isolation of symptomatic individuals, enhanced environmental cleaning using chlorine-based disinfectants, and careful food handling practices to avoid contamination. In outbreak situations, daily reporting to health authorities and the isolation or grouping of affected passengers and crew along with thorough sanitation prior to re-embarkation are required.

2.5 Classification Society Standards

Classification societies are independent entities authorized to conduct inspections and assessments of ships on behalf of flag states, shipowners, insurers, and other maritime stakeholders. Their role is to verify compliance with applicable regulations and to support the safe and efficient management of vessels.

In recent years, classification societies have played a critical role in formalizing shipboard infectious disease preparedness [16], [17], [18]. These standards, while voluntary, are often adopted by shipowners to demonstrate due diligence and to obtain certifications that enhance vessel credibility and compliance with international best practices. They offer a level of uniformity and assurance to port authorities, flag states, and the traveling public. By aligning with IHR obligations and WHO recommendations, classification society frameworks help bridge the gap between global health law and maritime safety regulation.

For example, the American Bureau of Shipping (ABS) developed a Guide for Mitigation of Infectious Disease Transmission Onboard Marine and Offshore Assets [19] in response to COVID-19. ABS acknowledges that both an asset's physical layout and its operational procedures can help reduce the spread of infectious diseases. The guide focuses primarily on a vessel's physical layout. It provides criteria for ship design and retrofitting to reduce transmission risks, which can result in granting the optional vessel class notation "Infectious Disease Mitigation – Arrangements" (IDM-A) [19]. To obtain this notation, vessels must be arranged with isolation cabins with anterooms, dedicated medical examination spaces, controlled access routes, and specialized ventilation systems. It also outlines requirements for cleaning protocols, personal protective equipment usage, and crew training compliance.

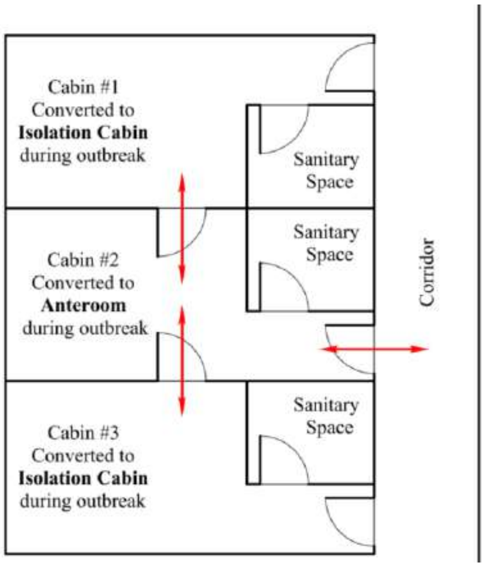

Figure 1: Example application of cabins isolation with shared anteroom (Source: [19]).

Bureau Veritas (BV) issued a similar document [20], which addresses pandemic response and infectious disease preparedness, particularly for passenger ships and ferries. The BV guidelines emphasize the development of comprehensive pandemic management plans, onboard health risk assessments, and enhanced sanitation procedures. They also provide checklists for ship operators to assess readiness before resuming service after an outbreak. The document focuses on critical areas where interventions are needed in case of a health emergency. It identifies three distinct levels of measures depending on the risk of outbreak. Systematic risk analysis forms the foundation for health risk preparedness, with shipboard spaces classified based on the specific hazards they pose and the functions they serve.

Table 1: Protection levels depending on the risk of outbreak (Source: [20])

Protection Level 1	• Normal sailing and normal risk of infection. • Standard prophylactic measures in place. • Plans and equipment provided in case of higher risk levels. • Items such as Outbreak Management Plan (OMP) are provided and understood by all required. • Prevention phase.
Protection Level 2	• Enhanced risk of outbreak. Company or relevant authority has recognised an enhanced risk of infection, as characterised by various government and Company actions such that active and passive measures are in place to avoid or control outbreak. • - Possible introduction of Social Distancing (SD) measures etc. • - OMP in effect to guard against outbreak. • - Actual infection onboard ship not known, but prepared for.
Protection Level 3	• Actual infection onboard, or demands for quarantine and similar measures required by Company, relevant authority or other stakeholders. • OMP in effect to guard against further infection and to reduce effects • Likely to require full SD, isolation and other highly restrictive measures.

2.6 Regional and Industry Guidance

Several regional and industry-specific bodies published guidelines tailored to the practical needs of maritime operators.

The joint COVID19 EU Guidance for Cruise Ship -Operations [21], first issued by the European maritime Safety Agency (EMSA) and the European Centre for Disease Prevention and Control (ECDC) in July 2020, outlines a goal-based, flexible framework for safely restarting cruise ship activities in EU/EEA waters. It addresses both shipboard and port-level measures, emphasizing the need for collaboration and coordinated planning among cruise operators, flag states, port authorities, and public health bodies. The EMSA/ECDC guidance aligns closely with IHR and WHO standards but also integrates European legal instruments such as the Schengen Borders Code [22] and the European Centre for Disease Prevention and Control (ECDC) frameworks [23]. In this document, a suite of tools and protocols are provided to support EU Member States manage communicable diseases at sea and in port. Key focus areas include:

- Risk-based management plans: Each cruise company should develop a tailored COVID19 risk assessment and mitigation plan. Similarly, ports and terminals should prepare their own operational plans and preset agreements between the two parties are required for handling onboard outbreaks.
- Public health protocols: Measures like physical distancing, hand hygiene, use of face masks in crowded settings, enhanced cleaning protocols form the core of shipboard and terminal operations.
- External verification: A noteworthy element is the guidance’s recommendation for optional external audits, to be performed by qualified third parties, to build mutual trust among stakeholders and ensure compliance.

In complementing WHO’s work, the International Chamber of Shipping (ICS), developed their Guidance for Ship Operators and [24]. This provides templates for shipboard COVID-19 management plans, outlines procedures for crew changes and evacuation, and seafarers’ mental health. The guidance has been regularly updated to reflect evolving knowledge on variants, testing technologies, and vaccination protocols.

In 2011, the EU SHIPSAN project developed the first comprehensive manual on Hygiene Standards for Passenger Ships [25]. This manual was updated in 2016 [26], and was formally adopted by the EU as a standard for compliance on passenger ships operating within their waters. Its primary aim is to support collaboration between the industry and competent authorities to reduce the risk of communicable diseases via the development and implementation of hygiene programs. The manual can help improve and maintain: a) the hygiene level on board passenger ships sailing to or within the EU waters; b) the level of compliance with hygiene standards that are included in the existing EU legislation; and c) the safety of food, water and environmental conditions for passengers and crew.

INTERFERRY, the global trade association for the ferry industry, provided targeted health and safety guidance for passenger ferries [27]. Recognizing the short voyage duration and high passenger turnover common in this sector, INTERFERRY's protocols emphasize practical measures such as contactless ticketing, controlled passenger flow, onboard signage, and crew health monitoring. Their recommendations are closely aligned with WHO and IMO guidance.

2.7 Gap analysis and Regulatory Challenges

Over the past few decades, a unified framework for managing health-related challenges onboard ships, particularly in the context of communicable diseases, has been under development. These advancements contributed to improved preparedness and response mechanisms within the maritime sector. Despite this progress, several critical gaps persist. A summary of developments is outlined in Table 2.

Table 2: Key challenges for the management of health diseases within the maritime industry.

Weak Surveillance and Reporting Systems	Surveillance and early-detection systems are essential for managing infectious disease outbreaks onboard ships. However, current practices largely depend on self-reporting by passengers or manual monitoring by crew members, with no standardized mechanisms for continuous health surveillance or systematic reporting of symptoms. In enclosed environments such as cruise ships, delays in identifying symptomatic individuals can significantly increase the risk of uncontrolled transmission and widespread outbreaks.
Limited Onboard Medical Infrastructure	Most vessels operate with limited medical personnel and small-sized medical facilities. The capacity to diagnose and manage infectious diseases at sea is extremely limited. Ships typically rely on remote medical consultations or need to wait for port access to provide appropriate care, which can delay critical interventions. Additionally, delivering diagnostic tools and medication to vessels is logistically complex and often hindered by regulatory constraints.

Limited Isolation Facilities	The confined nature of ship environments makes it difficult to separate large numbers of infected crew members or passengers. Most vessels are equipped with only a limited number of spaces which can serve as isolation (quarantine) spaces.
Public Awareness and behaviours	Health literacy and cultural perceptions of illness and hygiene play a critical role in the success of disease prevention measures. Variations in individual understanding, attitudes, and behaviours, shaped by cultural norms and educational backgrounds can significantly hinder the consistent application of health protocols. Moreover, language barriers and ineffective communication strategies further complicate the dissemination and adoption of these measures, particularly in diverse, multinational environments such as cruise ships.
Poor Coordination with Public Health Authorities	Coordination between ship operators, port authorities, and public health agencies can be ineffective due to non-standardized communication channels and delayed response and assessment of an ongoing developing situation.
Concerns over Data Privacy and Information Sharing	Data sharing is critical for disease surveillance and contact tracing. Health data shared in these contexts typically includes personal identifiers and medical information, which should be processed under the lawful basis of public interest in public health according to the GDPR in EU [28]. Data controllers (e.g., public health authorities) and processors (e.g., technology providers) must ensure appropriate safeguards, with retention limited to the duration necessary for public health purposes.

3. HS4U TECHNOLOGIES

3.1 Introduction

This section outlines the technologies investigated by the HS4U project. Each section starts with a brief overview of a technology's purpose and functionality. This is followed by a detailed account of the pilot activities carried out under Task 5.3, that highlighted the practical application, testing conditions, and preliminary outcomes associated with each technological solution.

To validate the performance of the equipment and HS4U technologies, the project established an onshore testing facility designed to replicate typical cruise ship accommodation areas. This setup enabled the prototype integration and evaluation of proposed technologies in a realistic and operationally relevant setting. The pilots testing activities were conducted from 5 to 9 May 2025 at the Technological and Cultural Park in Lavrion [29]. The experiments carried out during this period complemented full scale earlier onboard testing activities that took place onboard the cruise ship Celestyal [30].

The primary objectives of the pilot testing facility were to collect data under controlled conditions, validate algorithms and models used to simulate passenger behaviour, and identify additional requirements and unforeseen problems. The facility formed the basis for executing the HS4U scenarios developed in T2.2 [31], and measuring parameters related to the calculation of the defined technological KPIs [30]. Useful feedback was collected from participants who acted as passengers or crew members. The robot cabin served as a platform that can be used to demonstrate the impact of technological solutions to stakeholders. Figure 2 illustrates the virtual representation of the HS4U demo space. Figure 3 illustrates the HS4U robot cabin, a prototype environment designed for the pilot testing of integrated HS4U technologies. Table 3 provides an overview of the pilot testing scenarios, along with a brief description of the technologies involved and the underlying assumptions.

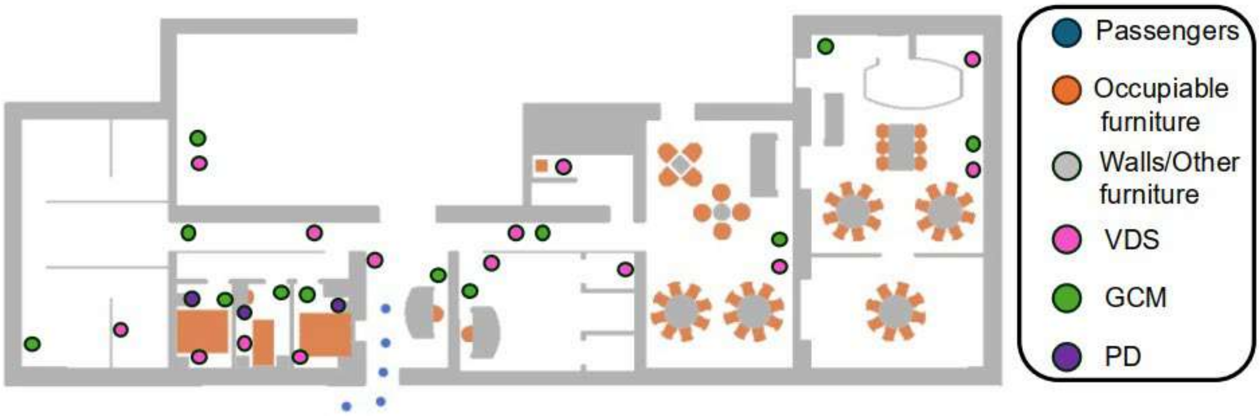

Figure 2: Virtual visualization of the HS4U demo space

Figure 3: Robot cabin. A prototype environment for pilot testing of integrated HS4U technologies

Table 3: HS4U Pilots testing scenarios

Scenario Number	Location	Assumed population	Assumed Hazards	Installed technologies
1	Cabin compartment	• 6 passengers • 4 crew members	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • Generic Communication Module • Passenger Dashboard • CDF platform
2	Embarkation station	• 35 passengers	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • Generic Communication Module • Check-in point device • CDF platform
3	Corridor	• 20 passengers	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • Generic Communication Module • CDF platform
4	Elevator	• 14 passengers queuing • 6 passengers inside	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • CDF platform
5	Staircase	• 20 passengers	• Airborne virus, • contact transmitted	• Antimicrobial coatings • Portable Virus Detection Sensor

			gastrointestinal disease	• Generic Communication Module • CDF platform
6,7	Dining and Entertainment room	• 50 passengers	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • Generic Communication Module • Probiotic emitter • CDF platform
8	Reception	• 8 passengers	• Airborne virus, • contact transmitted gastrointestinal disease	• Antimicrobial coatings • Portable Virus Detection Sensor • Generic Communication Module • Check-in point device • CDF platform

Throughout the experiments various performance indicators (KPIs, Table 4) were evaluated. Those focused on functional characteristics (e.g., responsiveness, accuracy), user experience, operational performance (e.g., disinfection effectiveness, compatibility with the marine environment), and cost-effectiveness. Given the diverse nature of the technologies tested different metrics were applicable to every solution. The experimental setup did not permit the use of actual biological agents for the simulation of high-risk scenarios. Therefore, it was not possible to comprehensively assess performance for technologies related to pathogen detection or disinfection. However, laboratory-level research on these technologies has been carried out by the respective HS4U project partners and is documented in Deliverable D3.1 [32]. This limitation stems from regulatory and safety requirements associated with experiments that may involve biological agents (e.g., bacteria, viruses, or genetically modified organisms) governed by EU biosafety and biosecurity legislation [33]. It is noted that usually biologically sensitive experiments are typically restricted to certified BioSafety Level laboratories (BSL), that meet stringent containment and operational standards not feasible in field testing environments [34].

During the experimental activities, participants were instructed to act as if they were in a normal ship environment and perform simple tasks such as moving through designated areas, touching surfaces or furniture, and engaging in basic interactions with other individuals. These actions aimed to support the collection of behavioural data and the monitoring of environmental parameters relevant to the early detection and management of infectious diseases. The number of participants varied between 10 and 50, depending on the specific design of each experiment. At the start of each session, participants were assigned a unique identification number, which remained consistent throughout the activities. This identifier was used to anonymously track participants' movements, behavioural patterns, and symptom-related indicators (e.g., body temperature, coughing incidents). The anonymized data were subsequently used to feed the HS4U data analytics tools (see Sections 3.8, 3.9, 3.10).

Table 4: Overview of Key Performance Indicators for HS4U Technologies

HS4U technology	Performance Indicators	Assessment
Antimicrobial coatings	Disinfection following surface contamination	Quantitative
	Coatings stability and durability	Qualitative
Viral Detection System	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
	Response time	Quantitative
Probiotic Emitter	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
	Disinfection action	Quantitative
WWED	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
	Sensitivity to virus detection	Qualitative
	Time required to collect samples in grey/black water	Quantitative
	Cost of sewage sampling collection	Quantitative
GCM	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
Passenger Dashboard & Check-in point	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
Passenger behavioural model	Predict passenger movement	Quantitative
Risk Assessment module	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
CDF platform	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
	User experience and perceived effectiveness	Quantitative
StreamHandler	Functional integrity, performance of core functions without faults or malfunctions	Qualitative
	Data streaming latency	Quantitative
	Self-diagnostics performance	Quantitative

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3.2 Antimicrobial coatings

3.2.1 Description of technology

Silver ions are widely recognized for their antimicrobial properties, effectively inhibiting the growth of various microorganisms through multiple mechanisms specific to each organism. This efficacy is well-supported by extensive scientific literature [35], [36]. However, a major challenge of silver ions is their instability under typical marine environmental conditions, where factors such as high salinity, humidity, chlorine exposure, and prolonged sunlight can significantly reduce their effectiveness.

CNT Lab’s patented *SynthAg* technology overcomes the inherent instability of silver ions by stabilizing them within nanostructured colloidal clusters. These clusters, formed through interactions with polar polymers, enhance bioavailability and antimicrobial efficacy while reducing cytotoxicity. This makes the technology particularly well-suited for hygiene-critical applications in maritime and other demanding environments, while no comparable coatings are used for similar purposes.

As part of the HS4U project, special focus was placed on shipboard surfaces that are either frequently touched or difficult to clean regularly due to operational constraints. These included public restroom fixtures such as stainless steel or chrome-plated taps, handrails, upholstered furniture including chairs, armchairs, sofas, carpets, door handles, and cabin switches made from various materials. To address the challenges of maintaining high hygienic standards on these surfaces, CNT Lab developed the following two specialized formulations based on *SynthAg* technology, each tailored for different surface types:

1. “LongLife Shield”: A transparent coating specifically designed for application on hard surfaces.
2. “AgTEX”: A water-based, fast-drying liquid solution formulated for use on textiles and other porous materials. This product can be sprayed on textiles, and once dried, silver ions link themselves to the fabric fibers, providing antimicrobial functionalities.

3.2.2 Pilot testing

To assess the efficacy of two advanced SynthAg-based antimicrobial formulations developed by CNT Lab, a series of structured, real-world tests were conducted on high-touch surfaces representative of cruise ship environments. The objective was to simulate realistic contamination scenarios and evaluate the products' ability to reduce microbial load under operational conditions.

To ensure the relevance and applicability of the antimicrobial efficacy tests, a representative range of high-touch surfaces commonly found onboard cruise ships was selected. These included elevator buttons, textile-covered chairs, handrails, carpeted flooring, and door handles. Each surface was deliberately contaminated through direct contact with unwashed hands from multiple individuals. In this way a consistent and practical assessment of the antimicrobial formulations under conditions that closely mirror actual use.

The microbial load was quantified using a professional bioluminometer equipped with ATP (Adenosine TriPhosphate) detection swabs. ATP, a universal biomarker of living cells, provides a reliable measure of biological contamination. Results were expressed in Relative Light Units (RLU), with higher values indicating greater pathogens contamination. The antimicrobial formulations were applied following standardized protocols developed by CNT Lab. Post-application microbial load was monitored at 30-second and 60-second intervals after deliberate contamination.

3.2.3 Key results and discussion

Both formulations demonstrated significant antimicrobial activity under the defined test conditions. A clear time-dependent reduction in microbial loads was observed across all treated surfaces, with greater reductions recorded at 60 seconds after contamination, as compared to after the 30-second interval. These time points were selected to reflect the typical frequency at which individuals may contact shared surfaces. Under this assumption, the rapid disinfection action of the coatings can play a critical role in interrupting the chain of microbial transmission through sequential surface contact.

The use of a “LongLife Shield” coating for hard surfaces, demonstrated an average reduction of 64% at 30 seconds, increasing to 89% at 60 seconds. The highest recorded performance was a 94% reduction on a stainless-steel handle after 60 seconds. This highlighted the how effective the technology may be on metallic surfaces commonly found in maritime environments. The “AgTEX” formula, for application on textiles and porous materials, exhibited an even higher efficacy. The average reduction was 74% at 30 seconds, reaching 94% at 60 seconds. Its best performance was observed on textile-covered chairs, achieving a 98% reduction after 60 seconds, indicating excellent compatibility with fabric-covered surfaces.

Table 5: Time-Based Antimicrobial Efficacy of SynthAg-Based coating on ship surfaces

Item	Product	Untreated surface measurements	Treated surface measurements			
		RLU (baseline)	RLU after 30s	RLU after 60s	Reduction after 30s	Reduction after 60s
Elevator Button	LongLife Shield	264	99	20	63%	92%
Textile-covered chairs	AgTEX	2637	298	43	89%	98%
Handrail 2	LongLife Shield	2144	431	240	80%	89%
Carpeted flooring	AgTEX	692	281	71	59%	90%
Handrail 1	LongLife Shield	2799	337	240	88%	91%
Door Handle	LongLife Shield	400	133	84	67%	79%
Stainless Steel Handle	LongLife Shield	320	118	19	63%	94%

Both coatings maintained their integrity throughout the entire testing period. No visible degradation, peeling, or loss of adhesion was observed. Additionally, no discoloration or change in colour was observed on any treated surface, confirming that the coating does not introduce visible aesthetic alterations to the materials. This supports the intended purpose of demonstrating that the coated surfaces remain visually unchanged to the end user. Compatibility tests with commonly used disinfectants revealed that chlorine-based products can compromise the coating’s stability. In contrast, peroxide-based disinfectants were found to be fully compatible and are already approved under existing cruise ship hygiene regulations. Overall, the pilot testing confirmed the potential of silver ion-based coatings in reinforcing antimicrobial protection on shared surfaces, establishing them as a valuable tool in the fight against pathogen transmission in high-touch environments.

In the future it is recommended that comprehensive investigation and testing is conducted to assess the compatibility of the subject coatings with commonly used plastic substrates such as polypropylene (PP) and polyvinyl chloride (PVC). This is particularly important considering the preliminary findings that indicate challenges in meeting fire safety regulations [37]. Any modifications or formulations should not only address material compatibility but also uphold the required standards for flame spread, smoke generation, and toxicity.

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3.3 Viral Detection Sensor (VDS)

3.3.1 Description of technology

Pathogen detection systems (PDS) can play a critical role in combating communicable diseases by enabling real-time, continuous detection of pathogens. This is because such systems are designed to directly detect genetic material (i.e., DNA/RNA) at the point of use. In this way early warnings of potential health risks, before symptoms manifest widely among individuals, may be possible.

Within the HS4U project, the Viral Detection Sensor (VDS) was developed to collect air samples from a ship's HVAC system and to analyse them for the presence of pathogens. The system, shown in Figure 4, is engineered for the real-time detection of airborne pathogens, including coronaviruses, by way of integrating bioaerosol collection, thermal RNA extraction, and sensor-based RNA identification. Airborne particles are initially drawn into the system via an external air pump, which channels the bioaerosols into a liquid-filled trap. The liquid trap serves to capture and suspend the particles in a medium conducive to subsequent analysis. Following this, the captured liquid is transferred to a heating station equipped with a stirrer, where the elevated temperature facilitates the release of RNA from any pathogens present. The processed liquid is then directed to the detection unit equipped with a specialized sensor which is capable of identifying the specific genetic sequences of known pathogens (e.g., SARS-CoV-2). Currently, the sensor is calibrated to detect only two target RNA variants, while in the future it could be adapted to accommodate more. Following positive identification, the VDS system is designed to automatically transmit analytical data to a compatible information management platform such as the CDF platform developed by the HS4U consortium (Section 3.10).

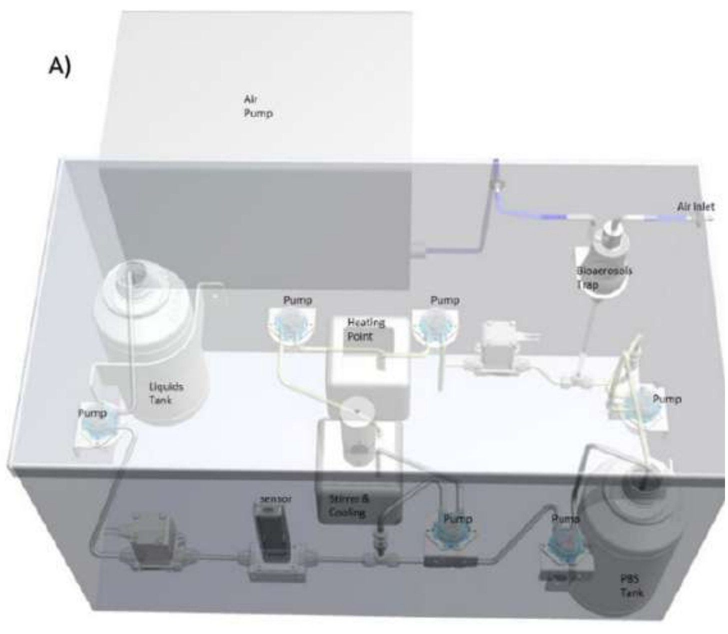

Figure 4: Illustration of the integration of a Viral Detection Sensor (VDS) system with an HVAC unit for airborne pathogen monitoring.

3.3.2 Pilot testing

During the pilot testing phase, a prototype VDS incorporating single-walled carbon nanotube (SWCNT) chemiresistors-based sensors was deployed. The VDS was installed and was fully operational throughout the testing period. It was used to continuously monitor airborne pathogens in real time for all tested scenarios (Table 3). Additionally, comprehensive air and liquid samples were obtained during all experimental scenarios to support the operation and evaluation of the VDS (Figure 6).

Figure 5: CDF Dashboard interface showing a real-time map of the demo space. A virus detection alert from the Cabins area is displayed, triggered by the VDS system. The alert highlights the cabin area and provides detailed event data to support immediate crew response.

Figure 6: VDS device installed in the entertainment room. The device was strategically positioned to sample air from vents, thus enabling effective real-time monitoring of airborne pathogens within the enclosed space.

Table 6: VDS device characteristics

Installation Status	Fully installed and operational
Functionality	Real-time detection of airborne pathogens via thermal RNA processing and VDS RNA sensor
Detection Radius	Connected to 4 HVAC vents for broader surveillance
Communication	Full integration with the CDF dashboard, including live notifications
Power Consumption	<50W
Operational Notes	Device remained stable and continuously updated system status to CDF throughout testing

3.3.3 Key results and discussion

Figure 7 shows the resistance - time profiles of SWCNT chemiresistors sensors used in the VDS developed by ECOSENSE, which include two types of sensors, namely P1 (red curves) and P2 (green curves). The X-axis of all panels included in the figure represents time (h-hours), while the Y-axis represents electrical resistance. Each panel corresponds to a different sensor and illustrates its respective output range.

The P1 sensors, engineered with a complementary sequence to viral RNA, serve as the positive probe. Upon interaction with the target viral RNA (e.g., SARS-CoV-2), a DNA/RNA hybrid duplex is formed. This binding event results in a measurable increase in resistance, indicating a positive virus detection. The P2 sensors, serve as reference probes, and they are designed to remain stable and return to baseline after the initial system stirring and mixing.

In the case presented in Figure 7, during the initial phase (0–0.37h, before the vertical, green, dashed line), the sensors stabilized maintain steady baseline values with minor fluctuations. Between the green and blue dashed lines, a stirring motor was activated, causing small baseline shifts. At 0.48h (blue dashed line), a lysed viral sample was introduced, followed by mixing until 0.55h (red dashed line), which induced a short-term transient signal change. After this point, the P2 sensors (green curves) returned to baseline values, confirming their role as negative controls with no detection. In contrast, the P1 sensors (red curves) showed a sustained deviation from baseline, indicating RNA binding and the formation of RNA/DNA duplexes. This sustained shift demonstrates a positive detection of viral RNA, confirming that the VDS successfully identified airborne viral genetic material under real-world conditions.

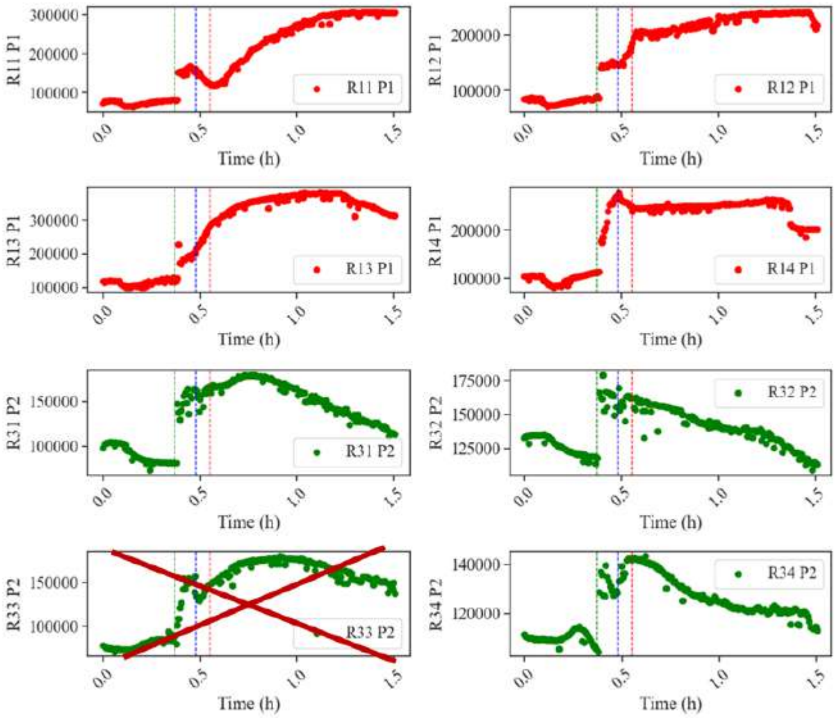

Figure 7: Real-time sensor output from the VDS system in the entertainment room

The deployment of the Viral Detection System (VDS) in maritime environments presented a series of technical and operational challenges that required targeted engineering adaptations. One of the primary concerns was the impact of environmental stressors, particularly high humidity and salt-laden air, which posed a significant threat to the integrity of sensitive electronics and sample preservation fluids. To mitigate these risks, the system design incorporated sealed enclosures and corrosion-resistant materials to ensure long-term reliability and data integrity under harsh conditions. Additionally, sensor accuracy was proved to be sensitive to interferences from the shipboard ventilation systems and temperature fluctuations. These factors introduced signal instability, affecting the precision of real-time bioaerosol detection and RNA extraction. Calibration protocols and environmental shielding were subsequently refined to enhance measurement fidelity.

Future development of the Viral Detection System (VDS) is centred on enhancing its adaptability, precision, and cross-sector applicability. A key focus is the miniaturization and modularization of the system, aimed at reducing its physical footprint and enabling flexible, plug-and-play installation across diverse zones within maritime vessels, such as cabins, crew quarters, and public areas. This modular approach is expected not only to simplify the deployment process but also to support scalable implementation tailored to specific operational requirements. Concurrently, efforts are underway to enhance the detection capabilities of the Viral Detection System (VDS) through targeted firmware and hardware upgrades. These improvements are expected to expand the spectrum of detectable pathogens and reduce the incidence of false positives, thereby enabling more accurate diagnostics and supporting informed decision-making. In parallel, the VDS is being adapted for deployment beyond maritime environments, evolving into a versatile tool for public health surveillance in sectors such as aviation, healthcare, and long-term care facilities. These settings share a critical need for real-time airborne pathogen monitoring, where the VDS can play a pivotal role in strengthening outbreak prevention and infection control strategies.

3.4 Probiotic Emitter (HS4U E-BIOTIC PRO)

3.4.1 Description of technology

Maintaining clean indoor air and surfaces onboard cruise ships is particularly challenging due to their enclosed environments and high traffic volumes. Areas such as cabins, fitness rooms, theatres, and dining spaces found on passenger vessels can accumulate biological contaminants, including bacteria, mold, allergens, and viruses. While conventional air purifiers typically address only airborne pollutants, they often overlook pathogens that reside on surfaces, within HVAC systems, and on shared objects. Traditional sanitation systems on cruise ships rely on chemical disinfectants, manual cleaning routines, and passive air filtration within HVAC systems. These methods tend to be reactive, addressing contamination only after exposure or outbreaks, and do not provide real-time data or continuous pathogen control.

The ECOSENSE probiotic emitter utilizes a continuous dispersion system to introduce a scientifically formulated probiotic formula namely bacillus-based blend [38], into HVAC systems. This process helps establish a stable microflora on surfaces and in the air, where the probiotics naturally outcompete harmful microorganisms by limiting access to essential nutrients, thereby contributing to a reduction in their presence. The ECOS air purification unit is designed for efficient and continuous dispersion of probiotics in enclosed environments. Table 7 presents the key technical and installation characteristics of the device.

Table 7: Probiotic emitter device characteristics

Unit Dimensions	Length: 0.32 m Width: 0.29 m Height: 0.50 m Weight: Approximately 6 kg
Mounting Requirements	Must be installed in an upright, wall-mounted position. The wall should support a minimum load of 20 kg. Placement should allow the power cord to reach a nearby electrical outlet without tension.
Installation Status	Installed and wall-mounted within the HVAC-connected.
Functionality	Continuously emits beneficial Bacillus-base probiotics into the air system for surface and air protection.
Operation Settings	The device features multiple programmable modes, tailored to the desired coverage area and refill interval ECOS provides case-specific guidance for configuration and installation.
Disinfection Radius	When connected to HVAC, the system can protect large areas up to 25,000 sq. ft., with measurable biotic presence on all surface types.
Power Consumption	Operates at approximately 15W.
Performance	Demonstrated uniform spatial distribution of probiotics, including difficult-to-reach areas such as vents, under seats, and corners

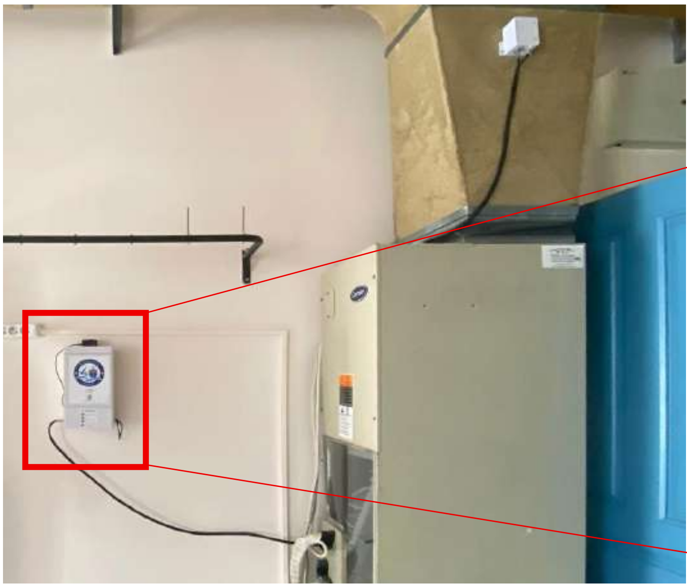

Figure 8: Wall-mounted probiotic emitter positioned in the entertainment room, connected to the HVAC system for optimal dispersion of beneficial microbes throughout the space.

Figure 9: Close-up image of the E-BIOTIC PRO device.

3.4.2 Pilot testing

Samples were systematically collected both prior to and following the probiotic emitter's activation to assess changes in microbial load and evaluate the efficacy of the treatment. Additionally, comprehensive air and liquid samples were obtained during all experimental scenarios to support the performance of the Probiotic emitter. To ensure personnel were not directly exposed to the probiotic treatment, activation of the Probiotic Emitter was deliberately scheduled after participants had concluded their activities within the Demo Space.

3.4.3 Key results and discussion

In the "before" samples – taken from the Pilot testing space "entertainment room" prior to the activation of the probiotic device – microbial cultures revealed a wide variety of contaminants, including Gram-negative pathogenic bacteria, fungi, and molds colonies, indicating a significant presence of airborne microbes in the untreated environment. Specific pathogens were tested, including gram-negative bacteria such as *Pseudomonas*, gram-positive bacteria such as *Staphylococcus*, and molds such as *Aspergillus*. These may be common in crowded indoor environments and pose health risks through air and surface transmission. Their presence indicates poor hygiene and potential for disease spread, while their reduction after probiotic treatment demonstrates the system's effectiveness in improving environmental safety and microbial balance.

Following the deployment of the ECOSENSE EnviroBiotics system, pilot-scale agar plate testing indicated a notable reduction in culturable microbial loads in the entertainment room, as illustrated in Figure 10. Prior to activation of the probiotic emitter, McConkey agar plates revealed approximately 35 colonies, including fungi and Gram-negative bacteria (e.g., Pseudomonas spp.), while LB agar plates showed a higher microbial load of approximately 236 colonies, reflecting diverse airborne microorganisms. After initiating the E-BIOTIC PRO system via the HVAC, follow-up air sampling revealed no detectable growth of pathogens on either medium. Only colonies consistent with the introduced Bacillus probiotic strains were observed. This highlights the efficacy of the ECOSENSE probiotic treatment in rapidly establishing a dominant and protective microbiome in the treated space. All samples were collected using a consistent air volume of 250 liters per plate to ensure comparability across conditions. However, these results represent a limited snapshot from a single treatment room and should be interpreted within the scope of feasibility testing under controlled pilot-scale conditions.

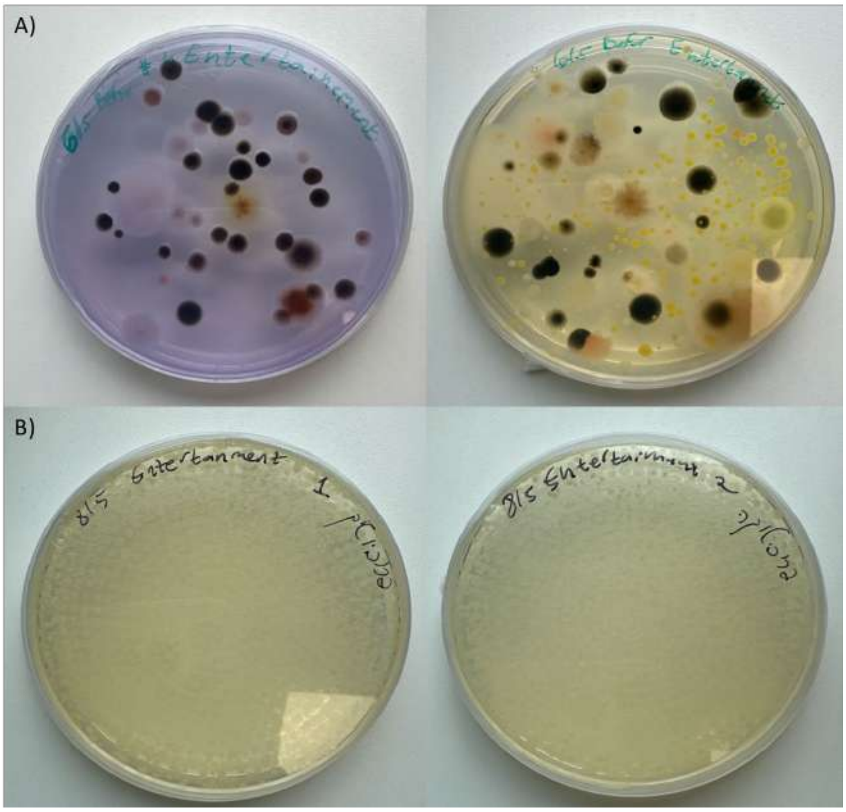

Figure 10: Comparative Assessment of Airborne Microbial Load in the Entertainment Room of the Pilots testing space. A) Before Probiotic Treatment on LB Agar Medium & MacConkey Agar Medium, B) After Probiotic Treatment on LB Agar Medium.

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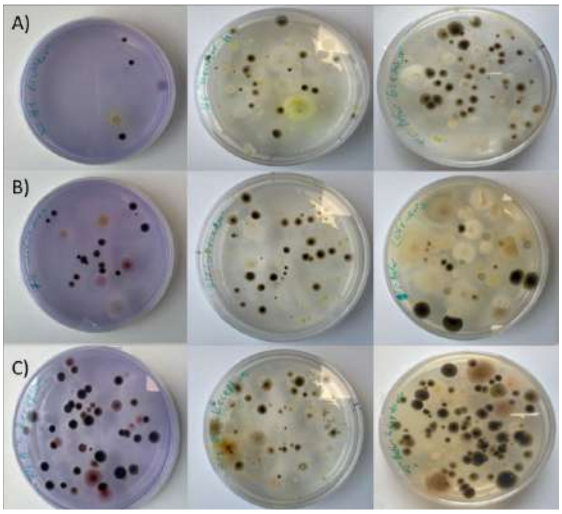
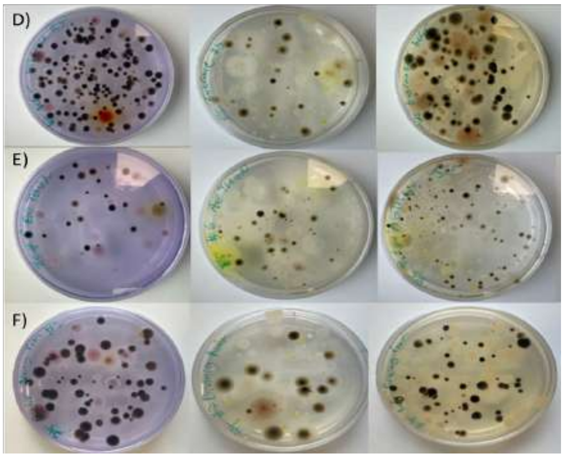


Testing area: Elevator (A)

Testing area: Corridor (B)

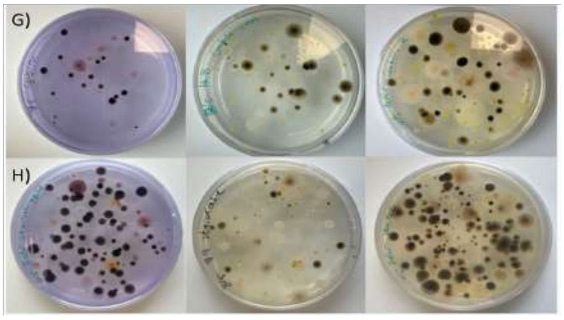
Testing area: Reception (C)



Testing area: Entrance (D)

Testing area: Transition experiment (E)

Testing area: Dining Room (F)



Testing area: Cabin (G)

Testing area: Staircase (H)

Figure 11: Microbial Load Comparison Across Pilots testing space scenarios. i) Left Column – MacConkey Agar: Illustrates microbial colonies, with a focus on gram-negative pathogenic bacteria, ii) Centre Column – LB Agar: Displays total microbial load, including fungi and general bacterial contamination, collected while participants were active in each scenario, iii) Right Column – LB Agar with Saline (Pre-Scenario Baseline): Shows microbial presence prior to any application, with dense and diverse colonies of fungi, Mold, and bacteria across all sample locations.

The performance of the Probiotic Emitter device was evaluated based on performance indicators addressing both operational reliability and treatment effectiveness. During the pilot testing phase, all system components functioned consistently, with no power interruptions or data losses, ensuring uninterrupted operation. The E-BIOTIC PRO unit demonstrated rapid responsiveness and maintained uniform probiotic dispersion across all areas of the Demo Space, including hard-to-reach zones, as confirmed through surface and air sampling.

In terms of effectiveness, the probiotic formula achieved rapid colonization and measurable environmental impact within hours of activation, contributing to quick risk mitigation. Post-treatment sampling revealed a significant reduction in surface contamination, validated by agar plate analysis, and confirmed the presence of only the intended probiotic strain. Additionally, the treatment was projected to reduce the risk of surface-transmitted diseases by up to 90%, attributed to consistent and targeted probiotic coverage.

Building on these promising results, the deployment of probiotic emitter device onboard ships also introduces a range of environmental and operational challenges. Maritime conditions, including salt-laden air, high humidity and fluctuating temperatures can have an impact on the performance of the probiotic formula used while the shipboard electrical infrastructure can generate large electromagnetic interferences, disrupting the device's sensors accuracy. To address these challenges, the ECOSENSE R&D laboratory developed a marine simulation chamber capable of replicating shipboard environmental conditions. This facility enabled extensive stress testing and optimization of the equipment prior to real-world deployment.

From an infrastructure standpoint, the system had to meet strict maritime standards, including anti-vibration mounts and corrosion-resistant components, suitable for shipboard environments. In addition, although the system was successfully tested in a demo environment, future deployments will require full certification processes, highlighting the need for compliance with safety-critical maritime regulations.

3.5 Waste Water Epidemiological Device (WWED)

3.5.1 Description of technology

A wastewater-based detection system has been identified as a viable approach for monitoring the presence of infectious agents onboard passenger vessels. During the SARS-CoV-2 health crisis, extensive municipal-level analyses demonstrated a strong correlation between viral RNA concentrations in wastewater and subsequent increases in hospitalization rates. Notably, elevated viral loads were detected in wastewater samples up to seven days prior to the onset of clinical symptoms and hospital admissions [39]. This lead time highlights the potential of wastewater surveillance as a proactive tool for health risk assessment and timely intervention in confined environments such as ships.

Within the HS4U project, a prototype sampling device was developed for use in cruise ship sewage systems. Considering the peculiarities and the complexity of such networks, the method and location for deployment of this device was investigated. It is noted that the device can support automatic and continuous sampling rates, while the sample analysis for pathogen detection, currently, is to be done manually. Thus, the experiments allowed for extracting results relevant to the presence of pathogens in wastewater. The device maker aspires that the integration of an automatic sample analysis unit similar to the VDS (Section 3.3) locally at the sample collection point, as well as the interface for data output and transmission to the CDF platform (Section 3.10) is feasible. However further field applications are essential to confirm this.

3.5.2 Pilot testing

The RWO's WWED, is designed to prepare and concentrate wastewater samples from cruise ships for the detection of viruses and pathogens like SARS-CoV-2. This section details the pilot program and demonstration process of the sampler. The experiments conducted aimed to validate operational efficiency in real scenarios. Complementary to the pilot testing activities were the demonstrations that showcased the sampler's automated operation. Results highlighted its seamless integration of components such as the buffer tank, prefiltration unit, membrane separation system, and control panel. The pilot testing campaign began with the preparation and assembly of the device at the RWO's production facility. Following successful assembly, the device underwent a comprehensive testing and troubleshooting phase. At first, the pressure vessels were hydrotested to confirm their structural integrity. Consequently, the control panel's cable routing and connections were thoroughly inspected, and the integrity and operability of all subcomponents were verified.

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(a)


(b)

Figure 12: a) Device assembly stage, b) Termination of the mechanical assembly of the device

Once initial tests were completed and the device was confirmed to be fully functional, it was transported and installed at the pilot's testing facility. All required systems and components for the RWO's WWED were prepared and made available for the demonstration of the technology. This included the sampler's automated operation components and integrated systems designed for wastewater sampling and concentration. The demonstration included the automated, unattended operation of the prototype device using tap water for testing purposes. The devices' component operations that were demonstrated are shown in the Table 8.

Table 8: Assessment of the device components during Pilot testing

Device Component	Assessment	Comment
Tanks	The level switches in TANK01 accurately monitored the fill level and triggered the pumps when the tank reached the appropriate capacity, thus ensuring a controlled and issue-free start to the operation.	
Prefiltration Unit	The prefiltration unit effectively removed remaining solids, safeguarding the downstream membrane system.	The filters showed no signs of clogging or bypass, operating perfectly to prepare the wastewater for the next stage.
Membrane Separation System	Both membranes performed optimally, with no fouling or pressure irregularities, thus demonstrating their ability to handle the wastewater effectively.	The membrane separation system consisted of two stages: Membrane 1: (pore size 500-800 nm) retained larger particles while allowing smaller particles, including viruses, to pass through as permeate. Membrane 2: (pore size 10- 20 nm) concentrated the viral particles in the retentate for analysis.
Pumps (PUMP01 and PUMP02)	Both pumps operated smoothly, with no unusual noise or vibrations, maintaining consistent flow and pressure throughout the demonstration	PUMP01 transferred the mock-up wastewater from TANK01 through the prefiltration unit and Membrane 1, while PUMP02 drove the prefiltered effluent through Membrane

Valves and Flow Control	All valves responded correctly to control panel commands, opening and closing as required to manage flow paths seamlessly, with no delays or malfunctions.	
Backwashing System	The backwashing system-maintained membrane efficiency by periodically reversing flow to clean the membranes. It activated automatically during the demonstration and performed without issues, ensuring the membranes remained free of fouling.	
Flowmeters and Sensors	The installed flowmeters provided accurate, real-time data on flow rates at critical points, displayed on the control panel, confirming that the system operated within expected parameters.	
Control Panel and System Monitoring	The control panel displayed statuses with nothing alarming triggered during the demonstration	

3.5.3 Key results and discussion

The demonstration began at the buffer tank, where wastewater undergoes gravity separation to reduce turbidity. Next, the prefiltration unit was showcased, effectively removing solids to safeguard the downstream membrane system. The heart of the technology, a two-stage membrane separation system, was then demonstrated. The first membrane, with a pore size of 500–800 nm, retains larger particles while letting viruses pass through, while the second, with a 10–20 nm pore size, concentrates viral particles for analysis. The presenter highlighted the system's automation, with pumps, valves, and sensors ensuring continuous, hands-free operation. The session wrapped up with a hands-on segment, where participants explored the control panel and examined the machine's components up close. The set-up pilot in the demonstrated area is shown in the Figure 13 below.

Figure 13: Wastewater epidemiological device installed in the area of demonstration

Attendees asked about the system's adaptability to various ship sizes, maintenance needs, and the possibility of adding real-time virus detection sensors.

Figure 14 illustrates the device's efficacy. As shown in Figure 14a, the untreated tap water is visibly turbid. After treatment, Figure 14b demonstrates a significant improvement in water clarity, indicating the device's effective performance.

(a) (b)

Figure 14: Demonstration of Machine turbidity removal effectiveness, (a) Un-treated tap water from the demonstration space. (b) Treated water from the demonstration space, the water is crystal

The performance of the RWO Wastewater Epidemiological Device was evaluated against three Key Performance Indicators (KPIs), namely:

- Sensitivity to virus detection,
- Time required to collect samples in grey/black water, and
- Cost of sewage sampling collection. These KPIs were assessed using data from environmental recordings conducted during the pilot phase, comparing the device's performance to conventional manual sampling methods.

The data required to calculate the KPIs were obtained during the environmental recordings campaign onboard the M/V Celestyal Discovery, between November 11 and 15, 2024. The campaign confirmed that sampling from the black water system is possible, and it can enable the early detection of viruses such as COVID-19 [30]. This offers a more proactive approach as compared to traditional methods that rely on self-testing or symptomatic individuals seeking medical attention.

At present, cruise ships do not implement water-based virus surveillance systems. Instead, virus detection typically happens through ad-hoc clinical assessments, initiated only when there is suspicion of viral presence onboard. A comparative overview of continuous virus monitoring onboard, with and without the use of the WWED, is presented below.

The time and safety implications of sample collection were thoroughly examined during the pilot phase. Manual sampling from vacuum-type sewage collection tanks was found to be labour-intensive and posed significant safety risks. The process of extracting samples from the bottom of these tanks is technically challenging. It may often result in spills that expose personnel to potential biological hazards. To mitigate these risks, personnel must wear full personal protective equipment (PPE) and follow strict safety protocols, a level of diligence that may be difficult to maintain consistently in cruise ship operations. Manual sampling requires approximately 5 minutes per sample, amounting to 6 man-hours per day (i.e., 12 sampling events, each involving 3 samples at 5 minutes per sample, plus 15 minutes of preparation).

In contrast, the RWO's WWED operates in a continuous, semi-batch mode, effectively eliminates the need for manual intervention. Its automated system ensures smooth sampling with minimal flow rate disturbances, that mitigate the risk of spills and associated health hazards. The integration of a pre-filtration unit and automated backwashing further enhances operational safety and reliability. This automation not only streamlines the sampling process but also addresses critical safety concerns, aligning with the HS4U project's objective of developing efficient and secure health monitoring solutions.

The cost of sewage sampling was assessed by comparing the manual sampling methods of the environmental recordings campaign [30], with the operational costs of the RWO's WWED. Manual sampling requires 6 man-hours per day, equating to 2,190 man-hours annually (6 × 365 days). At an assumed labour cost of €20 per man-hour, this results in an annual cost of approximately €44,000. In contrast, the RWO device incurs an annual cost of €2,000, comprising of €1,500 for equipment depreciation (based on an initial cost of €30,000 amortized over 20 years) and €500 for maintenance. This represents a 95% reduction in annual costs as compared to manual methods. The device's automated design and low maintenance requirements minimize labour and operation expenses. This cost efficiency aligns with the HS4U project's aim of delivering a scalable, economically viable technologies for maritime health surveillance.

Looking ahead, while the current system is designed to prepare samples for offline laboratory analysis, future development efforts will focus on integrating online sensors to enable real-time monitoring. The device is already equipped with connection points to support such enhancements. Achieving a fully automated, hands-off operation through the incorporation of additional sensors is a key objective in the continued evolution of the system.

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3.6 Generic Communication Module

3.6.1 Description of technology

The Generic Communication Module (GCM) is a multi-sensor management board designed to support the integration of various sensor types for real-time measurements. Its compact form, lightweight structure, and low-power design with wireless communication capabilities allow for flexible deployment in varied environments, that may require a single power connection. The primary goal of the GCM is to collect comprehensive health and environmental data. It integrates sensors that monitor various parameters such as air quality, levels of light, motion detection, and sound levels. By deploying these devices in strategic locations, the aim is to gather real-time data essential for evaluating spatial conditions that may influence the spread of diseases.

The Generic Communication Module (GCM) is a versatile device capable of interfacing with multiple sensors simultaneously. It includes integrated sensors for key environmental parameters (Table 9) and supports additional sensor connections via flexible interconnection options. Data is transmitted in a compatible format (e.g., using platforms like CDF, Section 3.10) using wireless protocols, with a sampling interval of 10 seconds. More technical and detailed information can be found in D3.1 [32].

Table 9:GCM built-in sensors

Parameter	Description	Range / Accuracy	Optimal conditions
Air temperature	-	-10 to 60 ºC, ± 0.45ºC	18 – 24ºC
Air humidity	-	0 to 95 %RH, ± 4.5%RH	30 – 60%RH
CO2	Carbon dioxide concentration	± 50.0 ppm	<1000 ppm
NOX Index	Relative intensity of nitrous oxides	1 to 500, ± 50 Index points	<150
VOC Index	Relative intensity of volatile organic compounds	1 to 500, ± 15 Index points	<250
Particulate matter	PM1.0, PM2.5	0 to 1000 µg/m3, ± 5 µg/m3	<5 ppm
Particulate matter	PM4.0, PM10	0 to 1000 µg/m3, ± 25 µg/m3	<15 ppm
Sound pressure level	Sound pressure Level of A-weighting filter in dB	35dB to 115dB, +/- 2 dB	-
Movement detection	Infrared proximity detection	Detection if value < 400	-
Proximity sensor	Obstacle distance measurement	0 to 0.5 m	-
Ambient Light	Measurement in Lux	1-64k lux	-

The measurement of environmental parameters such as temperature, humidity, Nitrogen Oxides (NOx), Volatile Organic Compounds (VOC), and Particulate Matter (PM) is intended to provide data on air quality within the space. This information can subsequently be used to assess the performance of the ventilation system and identify areas with poor air circulation. Such conditions are considered risk factors for the transmission of diseases onboard the vessel and are therefore considered in the real-time evaluation of onboard environmental conditions. The reference threshold values for optimal conditions presented in Table 9 were derived from WHO guidelines [40] and, where applicable, from sensor manufacturers' specifications [41]. These values were used as benchmark levels to guide the study and ensure that environmental conditions remain within optimal ranges. In cases where measured values exceed recommended thresholds, appropriate corrective actions are advised. These may include increasing the intake of fresh outdoor air to reduce CO_2 concentration, actively adjusting the HVAC system temperature to compensate for sudden fluctuations, or implementing air filtration measures when particle levels are elevated.

The sound pressure sensor is designed to effectively detect variations in sound pressure levels by measuring multiple acoustic parameters. These include slow and fast time-weighted averages, equivalent continuous sound energy, and frequency-weighted measurements based on the A-weighting scale, which corresponds to the human hearing response. Importantly, the sensor does not record audio, ensuring compliance with privacy regulations. Instead, it captures and processes sound pressure level data internally, providing real-time analysis across more than 15 distinct sound parameters without compromising personal privacy. Symptoms such as coughing, sneezing, and other illness-related sounds by capturing and analysing acoustic signals. These sensors measure variations in air pressure caused by sound waves and can distinguish between different types of noises based on their frequency, amplitude, and temporal patterns. By applying signal processing and machine learning techniques, the system can identify characteristic audio signatures of coughs or sneezes, differentiating them from background noise or other non-relevant sounds. This capability enables real-time monitoring of potential symptoms in shared spaces, such as onboard vessels or public areas, contributing to early detection of illness and supporting broader health and safety measures. More technical details can be found in D3.1 [32] and D4.1 [42].

The movement detection and light sensors can be valuable tools for monitoring human activity within a space. In the HS4U project, the movement detection sensors integrated on the GCM module have been used for detecting the presence and motion of individuals, thus enabling the system to track activity levels, estimate the frequency of visits within a room. With post processing of the sensors data, the number of occupants over time can be estimated. When combined with ambient light sensors, which can detect changes in lighting conditions, the system can infer contextual information, such as whether a room is actively used, to support space utilization analysis for the purposes of risk assessment (Section 3.9).

Figure 15: a) GCM device, b) GCM deployed in the space

The GCM device, Figure 15, features a compact form factor, that has a low power consumption (under 1 W), and is easy to deploy. The estimated cost for small-scale production is approximately €150. This includes all integrated sensors used to capture the parameters, but excludes the cost of data management and cloud infrastructure services.

3.6.2 Pilot testing

To support the recording of environmental data for the demonstration scenarios at the Technological Cultural Park of Lavrio (TCPL), a total of 13 GCM devices were deployed throughout the Demo Space (see Figure 16).

Figure 16: GCMs devices deployed in Demo Space

Figure 16 presents the location of GCM devices deployed within the Demo Space, indicated by green circles. The figure is based on a screenshot from the CDF platform dashboard (Section 3.10). Therefore, the background colours of the spaces carry no symbolic meaning. In addition to the Living Lab area, the figure also depicts the Robot Cabin space, located in way of the bottom-left corner.

3.6.3 Key results and discussion

Throughout the duration of the experiments, the GCM units could feed real-time data into the CDF platform. This enabled the automated risk assessment processes related to the spread of diseases. The results presented in this section aim to demonstrate the influence of specific events that may be relevant to practice. Notwithstanding this, results and their outcomes are based on the data collected from the scenarios defined in the demo space (Table 10).

Table 10: Scenario details

Scenario Number	Location	Date (day)	Start time (hh:mm)	End time (hh:mm)	Notable Events
1	Cabin compartment	08	13:10	13:32	• Cabin doors were closed at 13h18
2	Embarkation station	08	10:00	10:39	
3	Corridor	07	13:00		• We walked along the Hallway to the Entertainment
4	Elevator	08	14:03	14:07	• They left at 2.05pm and got in the Elevator again. • They waited in Reception space until 14h11 (cdf test)
5	Staircase	08	13:55	14:00	
6	Entertainment room	07	10:42	11:16	• 11h05: turn on HVAC • 11h08: The window has been opened
7	Dining room	07	11:38	12:20	• 11h32 people started coming in • 11h38 The GCM device was restarted • 11h41 GCM's ultrasonic sensor new direction • 11h58 The window has been opened • 11h59 open the door out • HVAC doesn't work the casino door was always closed +/- 12h35 came to eat here
8	Reception	07	10:20	10:40	

Figure 17 presents data collected by the proximity sensor during the experimental scenario number 8, conducted within the Reception Room of the testing facility. The vertical dashed lines indicate the start and end timepoints of the test. Each data point represents a distance measurement between the proximity sensor and an object within its line of sight. The Y-axis, expressed in cm, reflects the proximity of the object to the sensor, where lower values indicate closer distance. In this setup, it is evident that the objects are passengers, as minor fluctuations in the recorded distances over short time intervals are attributed to their movement relative to the sensor's fixed position. Data point clustering suggests conditions of increased crowding and therefore can be used to assess passenger congestion cases.

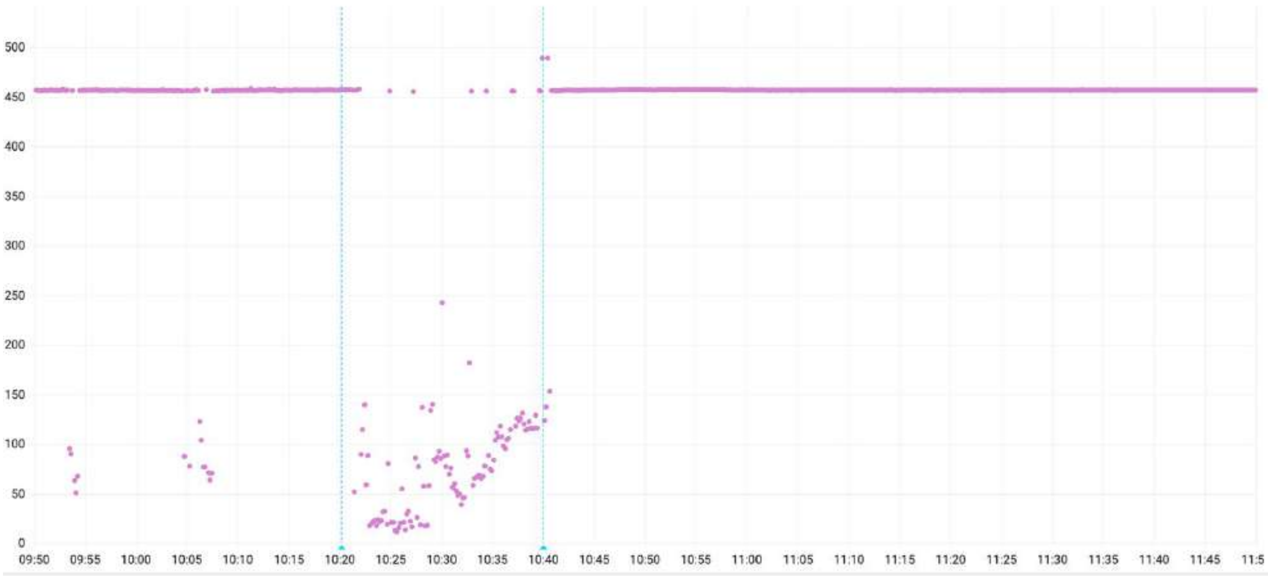

Figure 17: Use of Proximity sensor - Scenario #8 "Reception"

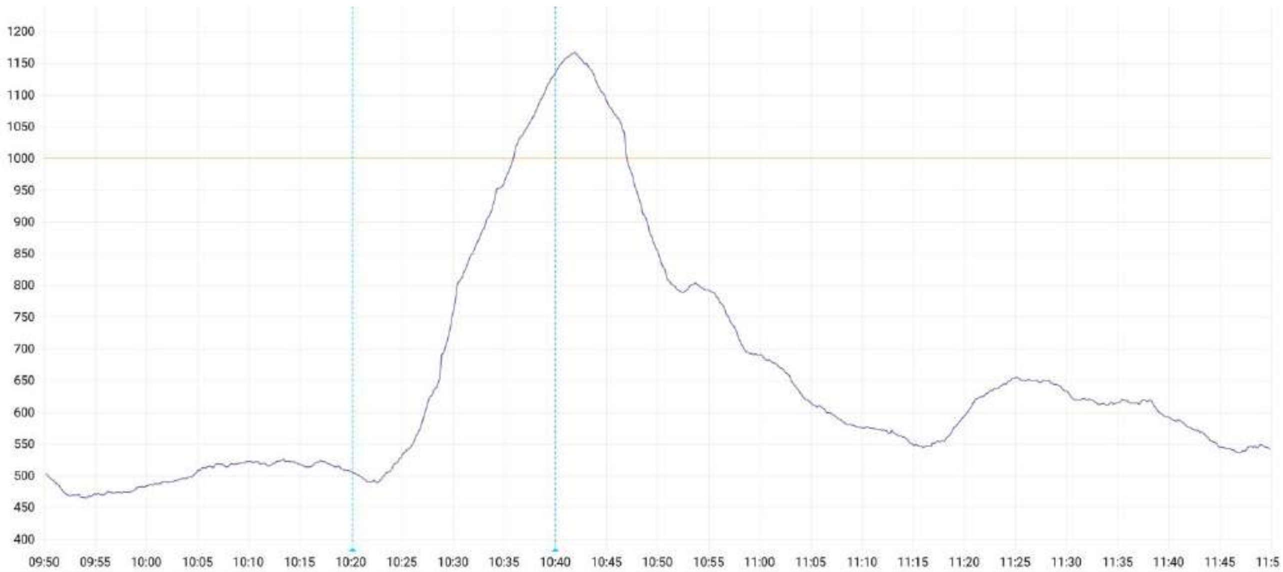

Figure 18: Use case of the Carbon dioxide sensor - Scenario #8 "Reception"

Figure 18, displays the data collected by the CO_2 sensor during the same experimental scenario conducted in the Reception Room (Scenario 8, Table 10). A threshold value of 1000 ppm, indicated by the yellow horizontal line, marks the point at which indoor air quality is deteriorating. The steady increase in CO_2 concentration observed within the same time frame as the crowding conditions identified by the proximity sensor reinforces earlier findings. This correlation enhances the reliability of the results and provides a quantitative tool for assessing congestion levels at points of interest.

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Figure 19 illustrates the evolution of CO_2 concentration in the Entertainment Zone during Scenario 7 (Table 10). The experimental activity began at 10:42, with several participants present in the room acting as passengers. Within approximately 15 minutes, by 10:56, the CO_2 concentration exceeded the recommended threshold of 1000 ppm, indicating a decline in air quality due to increased occupancy.

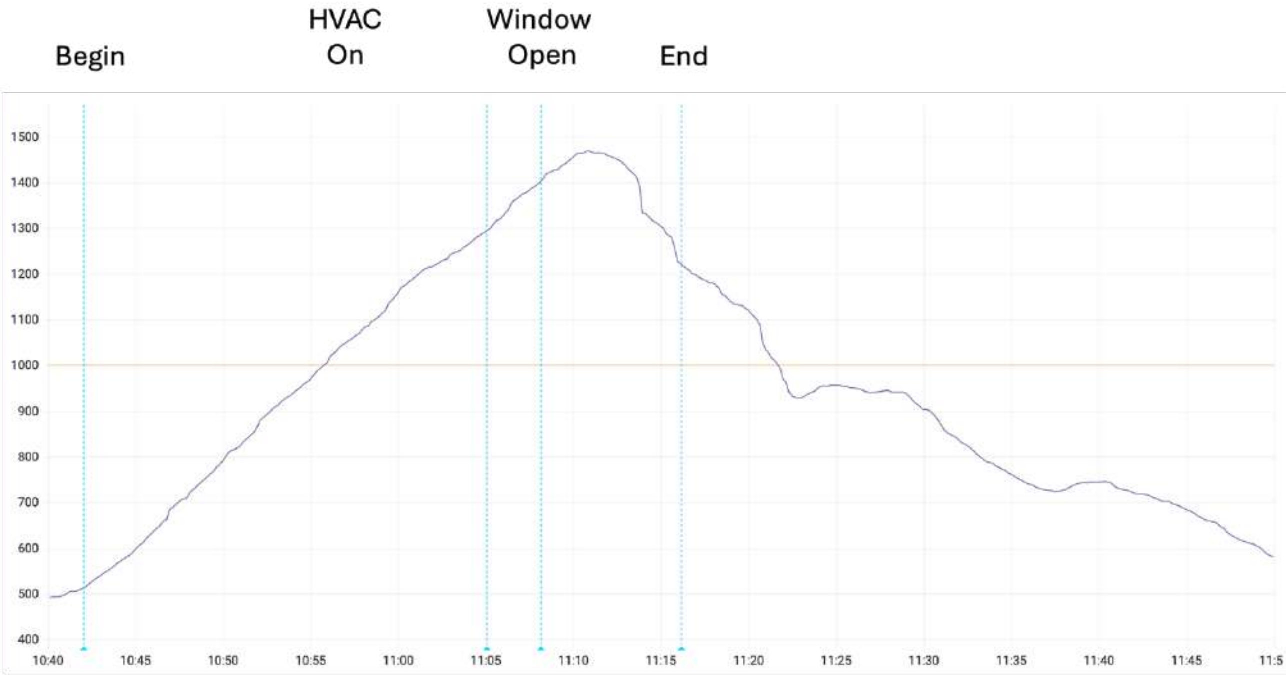

Figure 19: Use case of the Carbon dioxide sensor - Scenario #7 “Entertainment room”

The HVAC system was activated at 11:05, yet the CO_2 levels continued to rise, reaching a peak around 11:11. Shortly thereafter, the effects of mechanical ventilation, circulating fresh air into the space, began to take effect, reversing the deteriorating conditions. Within approximately 10 minutes, the CO_2 concentration returned to optimal levels. This finding demonstrates the effectiveness of the ventilation system in mitigating indoor air quality degradation caused by crowding.

Similar observations can be drawn from the data collected by the VOC sensor during the same testing scenario (Figure 20). From the onset of the experiment, the sensor recorded a sharp increase in VOC levels, surpassing the recommended thresholds within approximately three minutes. Notably, the decline in VOC concentration was significantly delayed, requiring more than 36 minutes after the activation of the HVAC system to return to acceptable levels. These findings suggest that, for the purpose of assessing indoor air quality under conditions of crowding, the VOC sensor may offer earlier and more sensitive indications of deteriorating air quality.

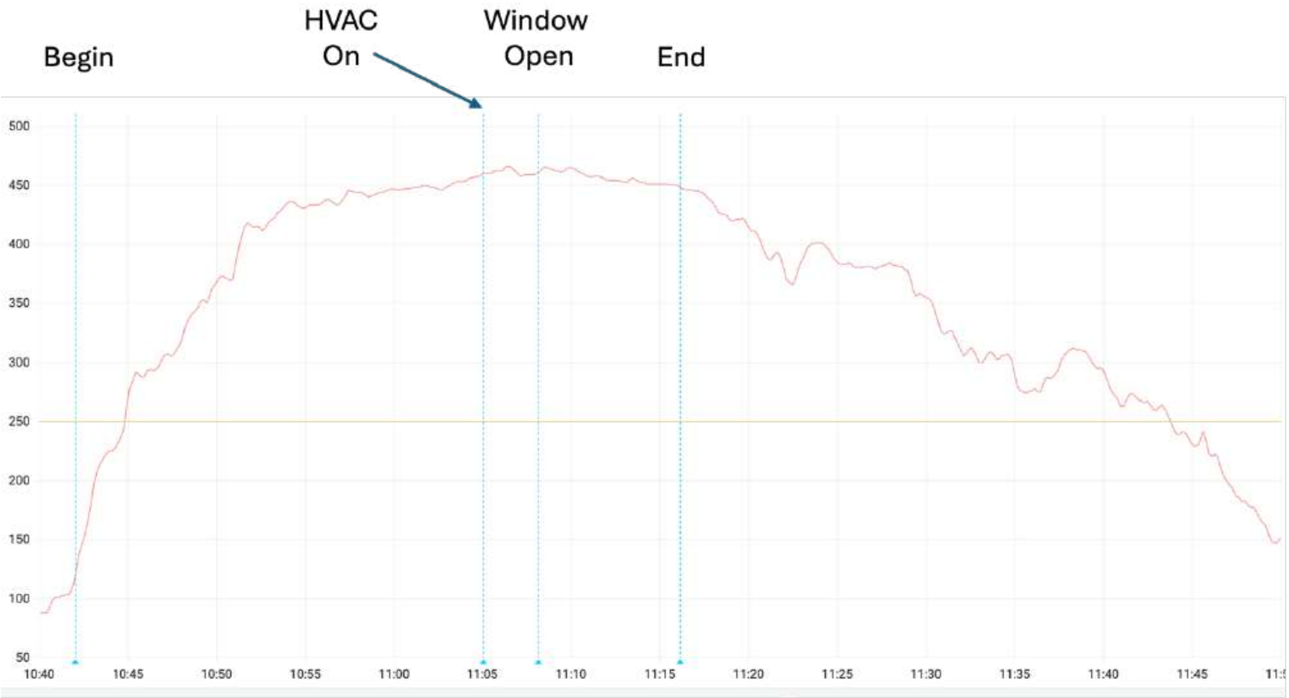

Figure 20: Use case of the VOC sensor - Scenario #7 "Entertainment room"

Figure 21: Use case of the Sound sensor - Scenario #6 "Restaurant"

Figure 21 illustrates the temporal progression of the equivalent continuous sound level (LAeq, measured in decibels), calculated using a 10-second time average, which corresponds to the sampling frequency of the GCM system. The data shown were recorded during experimental Scenario 6, conducted within the Restaurant area of the testing facility. Following the arrival of participants a sharp and expected increase in ambient noise levels was observed, reflecting the onset of human activity in the space. Throughout the scenario, the noise profile exhibited multiple fluctuations and occasional spikes. However, these variations do not appear to correlate easily with specific, identifiable events or actions within the environment, with the exception of one distinct event, which coincided with the opening of the main entrance door to the space at about 12h58. The conclusion of the experimental activity, which occurred at approximately 12:20, was marked by a notable and sustained reduction in noise levels, indicating the departure of participants.

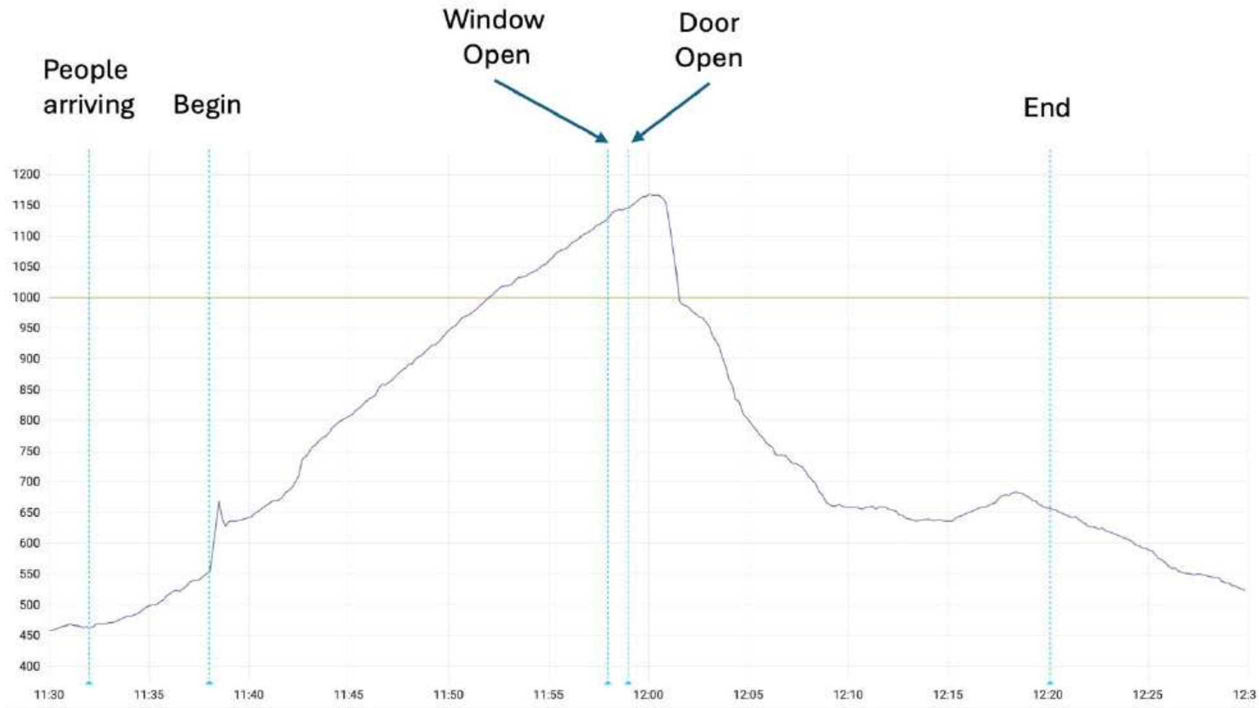

Figure 22: Use case of the CO2 sensor - Scenario #6 “Restaurant”

Figure 22 illustrates the progression of carbon dioxide (CO_2) concentration resulting from human presence within the “Restaurant” space during testing Scenario 6. Upon the participants’ arrival, CO_2 concentrations began to rise, exceeding the recommended threshold approximately 17 minutes after the experiment commenced. The concentration of CO_2 levels returned to advisable limits three minutes after the ventilation was activated. It is noted that the monitoring device restarted at 11:38, which caused a temporary spike in the recorded values and required a short period for the measurements to stabilize.

Finally, Figure 23 presents the progression of CO_2 concentration across the three designated cabin compartments (Cabin-1, Cabin-2, and Cabin-3), during Scenario 1 (Table 10), with each cabin occupied by a different number of individuals during the experiment. All three cabins were identical in size, and initial CO_2 concentrations were approximately equal at the start of the experiment. Notably, Cabin 1, which was occupied by four individuals, showed a faster rise in CO_2 concentrations, ultimately reaching values about 30% higher than the other two cabins by the end of the experiment. In contrast, Cabins 2 and 3, each occupied by two individuals, exhibited similar CO_2 accumulation patterns. These findings support the feasibility of using CO_2-based air quality sensors

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not only for monitoring ventilation and air quality but also for detecting human presence and estimating occupancy levels in enclosed spaces.

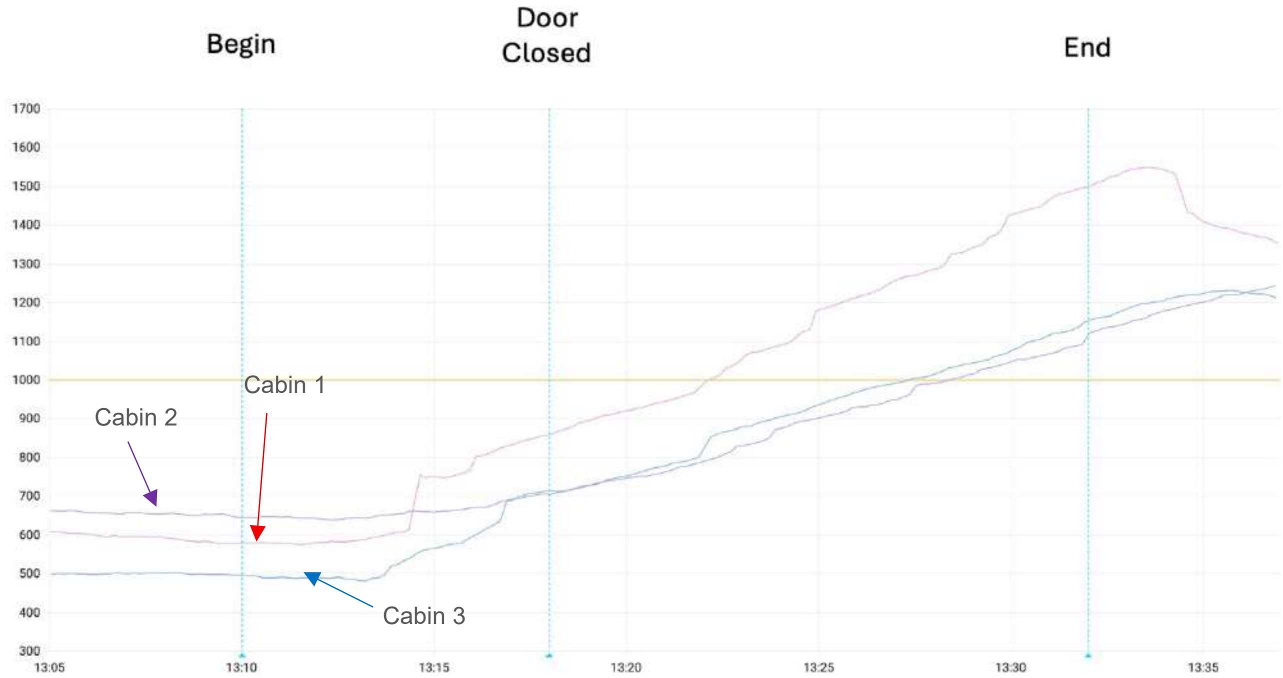

Figure 23: Use case of the CO2 sensor - Scenario #8 "Cabins Compartment".

3.6.4 Comparison to the existing protocols/ship equipment

The following table presents a comparison between existing ship protocols/equipment and the GCM. Key features such as sensor integration, real-time monitoring, communication protocols, data accessibility, and scalability are evaluated. Existing ship systems are often limited in scope, with sensor integration typically confined to specific subsystems like HVAC or navigation. In contrast, GCM supports the simultaneous connection of multiple heterogeneous sensors.

Table 11: Existing protocols/ship equipment vs GCM

Feature	Existing Ship Protocols/Equipment	Generic Communication Module
Sensor Integration	Often limited to specific systems (e.g., HVAC, navigation)	Supports simultaneous connection of multiple heterogeneous sensors
Real-Time Monitoring	Typically localized, with limited remote access	Full integration with online platforms for real-time remote monitoring
Communication Protocols	Proprietary or legacy protocols (e.g., NMEA 0183, Modbus)	Modern, flexible protocols (e.g., MQTT, REST APIs, Web Services)
Data Accessibility	Often siloed, requiring manual extraction	Cloud-enabled, accessible via dashboards and mobile interfaces
Scalability	Limited by hardware and integration complexity	Modular and scalable across different vessel types and sizes

A key advantage of the CGM system is its ease of deployment and low power requirements. However, to take advantage of the benefits of real-time data from multiple devices distributed throughout a cruise ship, integration with the existing ship infrastructure systems is essential. A significant challenge in this area is the prevalence of proprietary protocols and interfaces in current automation and communication systems. Those may necessitate the development of custom adapters or middleware software to enable integration of the GCM with the existing infrastructure, tailored to each specific case.

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3.7 Passenger Dashboard & Check-in point devices

3.7.1 Description of technology

The Passenger Dashboards and Check-In Point devices have been developed to serve as interactive interfaces for passengers onboard. These devices provide a user-friendly platform that supports the following functions:

- Check-in and check-out functionalities using simple barcode scanning or RFID based identification.
- Access to centralized information such as onboard and ashore activities with detailed schedules and locations.
- Optional collection of health-related data based on the passenger's consent, such as health questionnaires, body temperature, and self-reported symptoms. This information is used to support real-time health assessments through the Risk Assessment module (Section 3.9).
- Reception of real-time notifications from the crew about critical information including health-related alerts.
- Control over various cabin systems, including lighting, heating, air conditioning, and other appliances, consolidating functions that are typically managed through multiple physical switches.

Figure 24 shows the Passenger Dashboard, while Figure 25, presents the Embarkation Point Check-In device. Both are supported by web-based applications with dedicated user interfaces and are accessed via physical devices such as tablets. The estimated cost for each unit, based on small-scale production, is approximately €245. This includes a 12.1-inch Android tablet with Wi-Fi connectivity and an integrated thermal sensor for body temperature measurement.

Figure 24: Passenger Dashboard Device

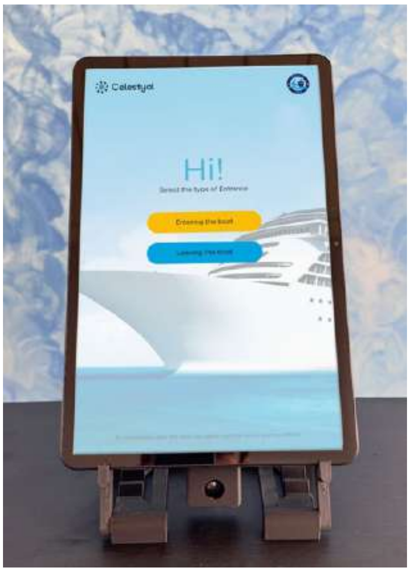

Figure 25: Embarkation Point Check-In device

3.7.2 Pilot testing

For the purposes of pilot testing, one Check-In Point device was installed at the main entrance of the testing facility, while three Passenger Dashboard devices were deployed within the individual cabin compartments. Figure 26 illustrates the layout of the Demo space, indicating the placement of the devices. Orange circles represent the Passenger Dashboards, and blue circles denote the Embarkation Point Check-In. Figure 27 shows their physical installation within the respective areas.

Figure 26: Passenger Dashboards and the Embarkation Point Check-In deployed in Demo Space

Figure 27: Reception space with devices

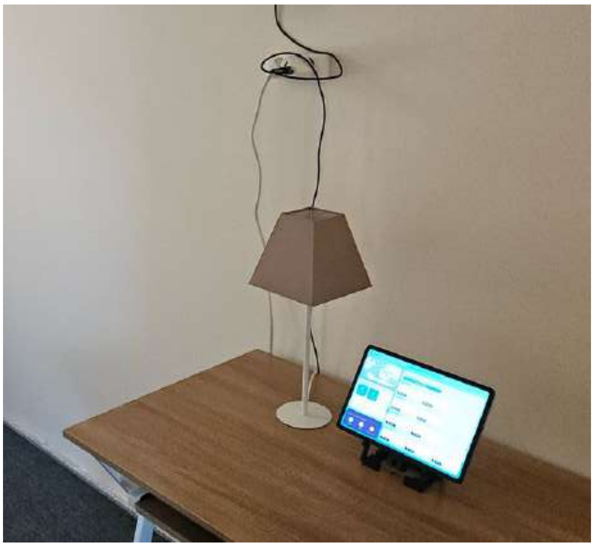

Figure 28: Cabin space with devices

3.7.3 Key results and discussion

The deployment of the devices within the demo space enabled a successful demonstration of their integration with the CDF platform, facilitating real-time data flow, as shown in Figure 26. The

Embarkation Check-In Point allowed for the measurement of passengers' body temperature during both check-in and check-out procedures, resulting in the collection of a significant number of temperature readings. More precisely, for the purposes of the experiment, more than 50 individuals acting as incoming passengers entered the designated entrance area and voluntarily participated in facial temperature measurements. The objective was to evaluate the reliability of the measurement process and to assess the device's effectiveness in detecting potential indications of elevated body temperature.

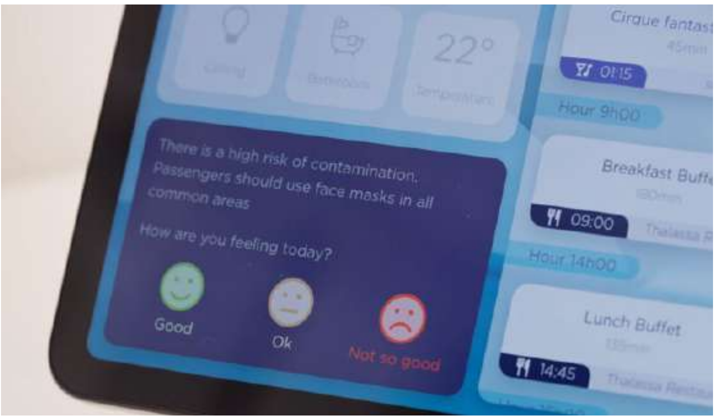

Figure 29: Passenger Dashboard integrated with CDF platform

Due to elevated ambient temperatures during the days of the experiments, facial temperature measurements proved to be inconsistent, occasionally producing false-positive readings indicative of fever. However, implementing simple precautionary measures such as allowing individuals to remain in shaded areas for a few minutes prior to measurement effectively mitigated these inaccuracies and improved the reliability of the readings. Despite this shortcoming, the embarkation check-in device offers several advantages over existing ship protocols and equipment (Table 12).

Table 12: Existing protocols/ship equipment vs Embarkation Point Check-in

Feature	Existing Ship Protocols/Equipment	Embarkation Point Check-In Device
Identity Verification	The need for an operator to identify the passenger	Self-scanning by passenger (through ID card)
Health check	Occasional manual temperature checks or none	Automated body temperature measurement at entry/exit
Check-In/Out Logging	Paper-based or isolated digital systems	Real-time digital logging integrated with online platform e.g., CDF platform
Disease Prevention	Reactive; relies on visible symptoms or crew observation	Proactive; screens for body temperature and flags potential health risks (health questionnaire)
Traceability/ Reporting	Fragmented or delayed reporting	Instant data capture and traceability
Passenger Experience	May involve delays and physical contact	Streamlined, hygienic, and user-friendly

The passenger dashboard device demonstrated comparable to the embarkation functionalities. Key advantages over existing onboard protocols and equipment are outlined in Table 13. The most notable innovative features are:

- Reduction of crew workload by automating routine communication and health monitoring tasks, particularly when health conditions indicate the need for closer observation.
- Support of medical response efforts by facilitating early detection of symptoms among both passengers and crew.
- Enhancement of passenger engagement by keeping individuals informed and actively involved in their own safety and comfort, directly from within their cabins.

Table 13: Existing protocols/ship equipment vs Passenger Dashboard

Feature	Existing Ship Protocols/Equipment	Passenger Dashboards
Information Delivery	Static displays, printed materials, or announcements	Real-time, personalized digital dashboards accessible via portable, touchscreen device
Symptom Reporting	Manual, often verbal or paper-based, with delays in response	Digital self-reporting interface for early symptom detection
Environmental Awareness	Not typically available to passengers	Shows real-time air quality, temperature, and other environmental parameters
Crisis Communication	Manual announcements, often delayed	Instant alerts and guidance tailored to each passenger's location and status
Integration with Other Systems	Fragmented; limited data sharing	Fully integrated with GCM and CDF platform
Feedback Mechanism	Rare or informal	Built-in feedback and reporting tools for passengers

3.8 Passenger Behavioural model

3.8.1 Description of technology

A simulation model was developed based on typical pedestrian models available from the civil engineering sector. The model was interlinked to an advanced biomedical model to simulate the transmission of infectious diseases. Considering passenger's characteristics (e.g., demographics, behavioural) as well as ship characteristics (e.g., spatial arrangements, points of interest, contact surfaces, etc.), this multi-model simulation aims to predict the spread of a disease in time, offering quantitative metrics useful for early-stage decision-making.

By applying this model to various ship areas and by analysing the impact of parameters such as crowd density and population capacity, valuable insights into the spread of communicable diseases can be obtained. These insights can inform operational decisions, including space capacity limitations, spatial modifications to influence movement patterns and contact frequency, as well as the enforcement of personal protective measures.

The simulation model is extensive and can be adapted to any ship configuration while aspiring to become the industry standard in the future for handling ship emergencies related to infectious diseases. The model was initially developed and calibrated using live testimonials of pilot partners' crew and interviews. The model was finalized by utilizing the data generated during the pilots testing (demo) period. At the end of the validation, the passenger model was able to predict passenger movement at 80% using pilot data.

3.8.2 Pilot testing

The aim of AETHON's experiment was to gather data to validate the Passenger Behavioural Model developed. The scenario assumed a disease outbreak occurring while passengers are clustered in high-traffic areas, such as the entertainment zone and the restaurant. In this context, crew members instructed passengers to return either to their cabins or to less congested locations.

The purpose of the model has been to simulate and predict passenger movement in terms of room occupancies. Passenger behaviour considered demographic and behavioural characteristics, which were assumed to significantly influence individual movement patterns. The specific factors incorporated into the experiment included:

- **Family Status:** Some passengers travel alone, while others are accompanied by family members, including children. It is assumed that individuals within the same group strive to stay together and move as a unit.
- **Age Category:** Participants were categorized into three age groups—child, adult, and old person. These categories were assigned randomly but in proportions based on demographics survey carried out in T2.1 [10]. Age is expected to impact mobility, as adults generally walk faster than children or elder individuals.
- **Compliance with Crew Instructions:** This variable captures whether individuals follow the evacuation instructions provided. It affects movement behaviour as non-compliant individuals may choose to remain at their initial locations.
- **Compliance with Social Distancing Requirements:** This variable reflects adherence to social distancing protocols applicable during a disease outbreak. Compliance is assumed to

influence the speed and manner of evacuation; without social distancing, crowded areas may be cleared more rapidly.

Specific instructions namely a unique ID, a family ID (to associate them with co-travellers), a starting and destination room, an age category, family status, and compliance behaviours (i.e., adherence to route and social distancing instructions) were created for each passenger. Instruction cards were generated for each participant to ensure clarity and to facilitate role comprehension. During the experiment, participants were required to move from their assigned starting point to their designated destination.

3.8.3 Key results and discussion

To measure room occupancy levels, raw data were collected via the Generic Communication Modules (GCMs, Section 3.6). The project partner Netcompany-Intrasoft (INTRA) subsequently developed a data processing module that leverages raw sensor inputs, such as CO_2 concentration and room temperature, to estimate occupancy levels with improved accuracy. The scenario began with high occupancy in the entertainment area and the restaurant (Table 14) and concluded with redistributed occupancy levels as shown in Table 15.

Table 14: Room occupancy at the starting point of the experiment

Room	Occupancy
Restaurant	25
Entertainment	10

Table 15: Room occupancy at the ending point of the experiment

Room	Occupancy
Restaurant	5
Entertainment	4
Medical Facilities	4
Reception	6
Elevator	4
Cabin-1	4
Cabin-2	4
Cabin-3	4

The experiment was successfully conducted twice. The first execution served as a test trial, while the second was considered the official run. Raw data were successfully collected from the Generic

Communication Modules (GCMs) during both executions and subsequently processed to derive room occupancy estimates. The occupancy measurements were recorded at a time resolution of 30 seconds.

As part of the previously conducted analysis on passenger movement dynamics (Chapter 6, D3.3 [43]), five predictive models were evaluated, as presented in Table 6-14 of the same deliverable. The evaluation metric used was the Mean Absolute Error (MAE), with the best performing model demonstrating an error of 2.09 passengers. Given this result, and considering that a total of 35 participants were involved in the pilot experiment, the model's accuracy can be quantified as follows:

$$\frac{Number\ of\ participants\ -\ Model\ Error}{Number\ of\ participants} = \frac{35\ -\ 2.09}{35} \approx 94.0\%$$

Thus, following the analysis of the collected pilot data, the results indicate that the passenger model achieved a prediction accuracy of 94.0% in forecasting passenger movement. To make use of this capability, AETHON developed the Passenger Movement Component, which is integrated into the CDF platform (Section 3.10). This component makes use of the VADERE crowd simulation framework to rapidly predict passenger trajectories and estimate the time required for each passenger to reach their destination. When combined with the Risk Assessment module (Section 3.9) forms a multi-modal model. This enhanced model utilizes VADERE not only to estimate passenger movement (trajectories and arrival times), but also to simulate disease spread dynamics, based on the findings reported in D3.2 [44]. In the event of a disease outbreak, CDF users can execute one or more scenarios involving all passengers, and within minutes, each simulation completing in under 20 seconds, obtain predictive insights into the potential spread of the disease.

Comparison to the existing protocols/ship equipment

Cruise lines and other passenger ships follow well-established emergency and health protocols (muster drills, medical screenings, isolation areas, etc.). However, these procedures do not include systematic movement tracking or flow modelling. During an outbreak, crews rely on existing plans (e.g., self-testing, quarantine, cleaning, mask-wearing) issued by bodies like WHO or CDC and use tools like passenger databases and cabin counts to monitor situations. There is no routine use of specialized equipment to measure room occupancy or pedestrian flows – crew members' observation and CCTV are used for general surveillance. In practice, crew members track passenger movement informally (e.g., counting people in muster stations, noting crowding in halls) rather than using detailed data. No evidence was found that cruise operators routinely run experiments or simulations of passenger movement as part of their health protocols.

Academic and industry research on ship passenger movement has primarily focused on emergency evacuation and crowd-safety modelling rather than routine health-related monitoring. Large-scale projects such as the EU-funded SAFEGUARD [45] project conducted full-scale sea trials on ferries and a cruise ship, where volunteers wore tracking badges and their movements were recorded with infrared tags and cameras. These data provided empirical validation for evacuation models and informed updates to safety regulations. However, such efforts were limited to one-off research trials and were not adopted into operational practice. Beyond these initiatives, most relevant studies originate from transportation or emergency evacuation research, sometimes motivated by high-profile events such as the Diamond Princess COVID-19 outbreak [46]. These studies typically rely on computer simulations or laboratory experiments and have not been translated into standard procedures on cruise ships. In short, no evidence was found of cruise companies independently implementing timed occupancy or pedestrian-flow experiments in daily operations.

A similar picture emerges for other types of passenger vessels, such as ferries. While some academic work has examined walking speeds in moving corridors or evacuation behaviours, ship operators do not routinely measure or simulate passenger flows. By contrast, sectors such as airports and subways have integrated more advanced crowd simulations and occasional field trials. Overall, the maritime industry lacks automated tools and protocols for real-time occupancy monitoring. Against this backdrop, the pilot experiment conducted in this project, measuring room occupancy every 30 seconds as 35 volunteers moved between compartments, represents a novel methodological contribution. Unlike the qualitative observations and post-facto tracing typically relied upon at sea, this study generated quantitative flow data under controlled conditions. To the best of current knowledge, such data-driven analysis has not previously been implemented by cruise operators, highlighting both the originality and potential value of the approach for outbreak response planning.

Challenges and future development

A major challenge faced during the study has been to ensure data quality while adhering to strict data protection regulations. GDPR [28] compliance prevented the use of personal tracking devices. Therefore, the research team relied on indirect occupancy estimates derived from sensor data.

Despite this limitation, all planned experiments were successfully conducted. Also, it was demonstrated in [43] that even with lower-quality data gathered in the pilot experiments pedestrian simulation models can achieve meaningful levels of accuracy. The reduced fidelity of the input data inevitably constrained model performance, thus highlighting the urgent need for technological solutions that offer accurate measurements while fully respecting privacy regulations.

Future work should focus on transition from controlled building environments to experiments conducted on actual cruise ships. This would enable testing of the HS4U solution under more realistic and operational conditions.

Applications in airports, hospitals, public buildings, and other complex indoor spaces are not only feasible but also urgently needed. As such, this work lays the foundation for a broader, scalable approach to modelling pedestrian behaviour in support of public health and safety across diverse domains.

3.9 Risk Assessment module

3.9.1 Description of technology

Risk Assessment (RA) in the context of the HS4U project refers to the process of collecting, analysing, and interpreting data to estimate the likelihood and severity of infectious disease transmission events in enclosed maritime environments. The RA module developed in Task 3.2 [44], is a core software component of the CDF and is responsible for evaluating real-time data from multiple sources to support timely and informed decision-making for outbreak mitigation.

The RA module is built on a knowledge-based approach, specifically a fuzzy rule-based inference engine, which encodes expert knowledge and evidence from epidemiological studies, biomedical simulations, and literature into interpretable rules [47]. These rules guide the module in assessing risk levels and recommending appropriate control actions.

The module integrates diverse data inputs, including clinical indicators captured by specialized sensors (e.g., fever via thermal sensors, cough detection via audio sensors using the GCM - Section 3.6) installed in ship areas, demographic attributes from the ship's information system (e.g., vaccination status), and environmental parameters (e.g., occupancy levels and HVAC conditions). These inputs are processed to generate a risk index, accompanied by a confidence level that reflects the reliability of the assessment.

Biomedical simulations may enhance the confidence of the risk assessment process, *e.g.*, by simulating how an infectious disease may spread in a monitored area. Once estimated, the risk index is communicated to the CDF platform (Section 3.10), where it can be visualized and used to inform crew actions and system-level interventions. This modular and interpretable framework enables proactive health monitoring and supports the integration of the RA module into the broader smart ship infrastructure envisioned by the HS4U project.

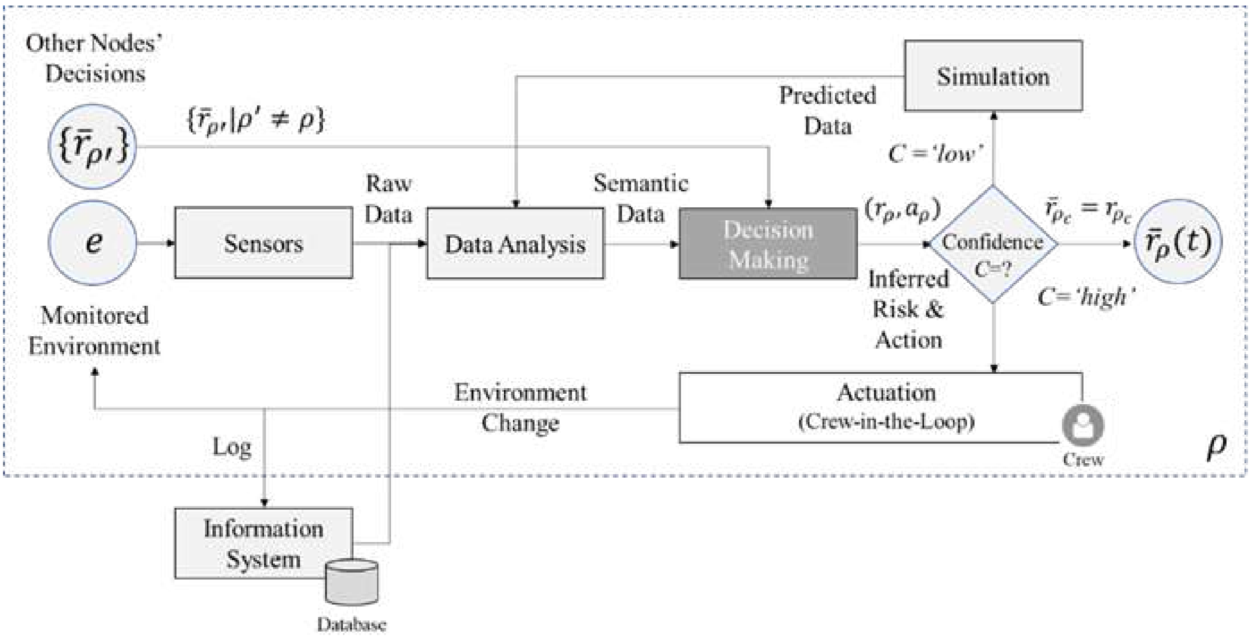

Figure 30: Generic, closed-loop model for risk assessment.

3.9.2 Pilot testing

The aim of the pilot testing was to evaluate the effectiveness of the fuzzy rule-based RA module for short-term disease transmission in cruise ship environments [44]. The RA module leveraged data provided by the CDF to estimate the risk of infectious disease spread and propose relevant actuations. The pilot testing was designed to simulate realistic onboard scenarios involving varying environmental conditions and passenger distributions across different ship areas, such as restaurants, cabin corridors, lounges, and restrooms. Each scenario aimed to assess how specific risk factors, such as overcrowding and symptom frequency, affect the transmission risk as calculated by the RA module. The module processed sensor data in real time and applied a fuzzy inference engine built on expert knowledge and literature-based indicators to generate a risk index for each scenario. The goal of the pilot was to validate the RA module's ability to detect early signs of disease transmission and recommend appropriate mitigation actions to the crew.

3.9.3 Key results and discussion

The pilot testing of the fuzzy rule-based RA module demonstrated its effectiveness in identifying and quantifying disease transmission risks across realistic onboard scenarios (Table 3). The outcomes of the pilot confirmed the module's responsiveness to key transmission factors. For example, scenarios involving high passenger density, exposure time, or coughing frequency consistently resulted in elevated risk scores, which aligned with the expected outcomes defined in the pilot plan. The module successfully identified high-risk zones and triggered appropriate alerts to the crew via CDF, demonstrating its potential for integration into smart ship operations.

Table 16 summarizes the results obtained during the deployment of the fuzzy rule-based RA module in the physical demo environment (real demo space risk), in comparison with a) the empirical risk, estimated by maritime experts, and b) the simulation-derived risk, estimated from agent-based simulations in the virtual demo space (Figure 2), where the pilot scenarios were reproduced under controlled conditions in line with D3.2 [44].

Table 16: Comparison of different methods of RA for different pilot testing scenarios

Scenario Number	Location	Risk based on Experts	Risk based on Virtual Demo Space Simulations	Risk Estimated in the Real Demo Space
1	Cabin compartment	HIGH	HIGH	HIGH
2	Embarkation station	HIGH	HIGH	HIGH
3	Corridor	MEDIUM	HIGH	HIGH
4	Elevator	MEDIUM	MEDIUM	MEDIUM
5	Staircase	MEDIUM	MEDIUM	HIGH
6	Dining room	MEDIUM	MEDIUM	MEDIUM
7	Entertainment room	HIGH	HIGH	HIGH
8	Reception	MEDIUM	HIGH	HIGH

Overall, the three risk estimation approaches indicate a strong alignment across most of the tested scenarios, with only minor variations in risk levels. In particular, the simulated and the real demo space RA tend to yield higher risk estimates compared to the empirical assessment in certain settings (e.g., corridor, staircase, and reception). Nevetherless, this behaviour is consistent with the system's design priorities, emphasizing high sensitivity to potential epidemic outbreaks.

Moreover, the pilot validated the module's ability to operate across diverse spatial configurations and user cases, from enclosed elevators and cabins to open entertainment areas. The consistency between the module's risk estimations and the observed scenario dynamics supports its utility as a decision-support tool for proactive outbreak management in maritime environments. These results provide a foundation for further refinement and deployment of the RA module in real-world cruise ship settings and other high-occupancy maritime domains.

Comparison to the existing protocols/ship equipment

Current ship protocols for epidemic control primarily rely on manual health checks, paper-based symptom logs, and generic containment procedures (e.g., ship-wide lockdown). These methods often lack timely insight, context awareness, and tailored responses to evolving health risks. In contrast, the proposed RA module introduces a real-time, sensor-informed risk assessment mechanism integrated into the ship's CDF. It leverages fuzzy logic to reason under uncertainty, accounting for contextual factors such as space usage, HVAC conditions, exposure duration, and symptom patterns like coughing or elevated temperature.

Based on the inferred risk levels, the module recommends targeted mitigation actions, such as localized isolation, ventilation adjustments, or crew alerts, that enable a more precise and proactive outbreak control. Unlike static, rule-of-thumb guidelines, the RA module dynamically responds to changing input data and supports early-stage detection and decision-making with explainable outputs. Its modular design ensures compatibility with a wide range of sensor configurations and vessel layouts, making it scalable across different maritime environments while preserving user privacy through area-level data aggregation.

Challenges and future development

The development of a biomedical risk assessment framework in Task 3.2 addressed the unique challenges posed by the enclosed and highly interactive environment of cruise ships, where infectious diseases can rapidly propagate. While the framework successfully integrated simulation-based modelling, sensor data, and disease transmission dynamics into a coherent risk assessment module, its broader deployment raises several practical and technical challenges.

A significant challenge is the lack of real-world data on short-term interactions between infected and healthy individuals in shipboard settings, which made the development of robust data-driven RA models particularly difficult. This was addressed by utilizing a knowledge-based approach, *i.e.*, a fuzzy rule-based module. Nevertheless, the deployment of the proposed RA module on actual ships could enable the collection of real-world data, allowing future integration of interpretable deep learning models into the existing RA framework and improving the risk estimation capabilities of the module, while preserving transparency. Additionally, adaptive calibration mechanisms could be developed to automatically tune the RA module based on environmental context, historical accuracy, or emerging infectious diseases.

The variability of available sensor infrastructure across different vessel types affects the resolution and completeness of real-time data, posing a significant challenge for deploying the RA module in diverse maritime settings. Given that most commercial vessels currently rely on limited and heterogeneous sensor setups, future deployments will need to accommodate varying levels of data availability and quality. To address this, the module's modular design allows it to adapt to different vessel layouts and equipment configurations. Building on this flexibility, future work could involve deploying the RA module in commercial cruise ships and other high-occupancy maritime environments, such as ferries, offshore platforms, or naval vessels. This would allow for further evaluation of the module's scalability and generalizability. Ethical and privacy concerns were another challenge. The RA module addresses ethical and privacy concerns by relying on aggregated, non-identifiable data provided through the CDF, ensuring that individual privacy is preserved while enabling accurate, area-level risk estimation. However, techniques such as federated learning and edge computation could also be explored in future work to ensure regulatory compliance and preserve user trust. Furthermore, incorporating stakeholder feedback throughout module design and evaluation can further support commercial adaptation.

Overall, the developed RA module has laid a strong foundation for intelligent, sensor-informed health monitoring of infectious diseases in maritime contexts, and its modularity ensures broad applicability for proactive outbreak mitigation and enhanced safety in the maritime sector.

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3.10 Collaborative Digital Framework platform

3.10.1 Description of technology

The CDF platform represents a core software innovation of the project, designed to serve as a unified data integration solution. Its primary objective is to consolidate and ingest data from both software-based sources, such as the passenger behavioural model, biomedical model (Section 3.8), and risk assessment modules (Section 3.9). Sensor data made available via the GCM (Section 3.6) and user input through the dashboard (Section 3.7), into a single, cohesive platform are also considered. The CDF supports real-time data streaming and offers a graphical user interface.

The dashboard (Figure 31) functions as the central interface for real-time monitoring, event management, and incident response. It provides users with an overview of system activity and facilitates efficient decision-making through the following key features:

1. Sensor positioning
    a. Displays the precise location of all active sensors, enabling users to easily identify placements and enhance situational awareness and monitoring accuracy.
2. Event-sensor room coupling
    a. Visually associates detected events with the specific rooms in which they occur.
    b. Utilizes color-coded indicators to distinguish between event types and severity levels, enabling quick assessment and prioritization.

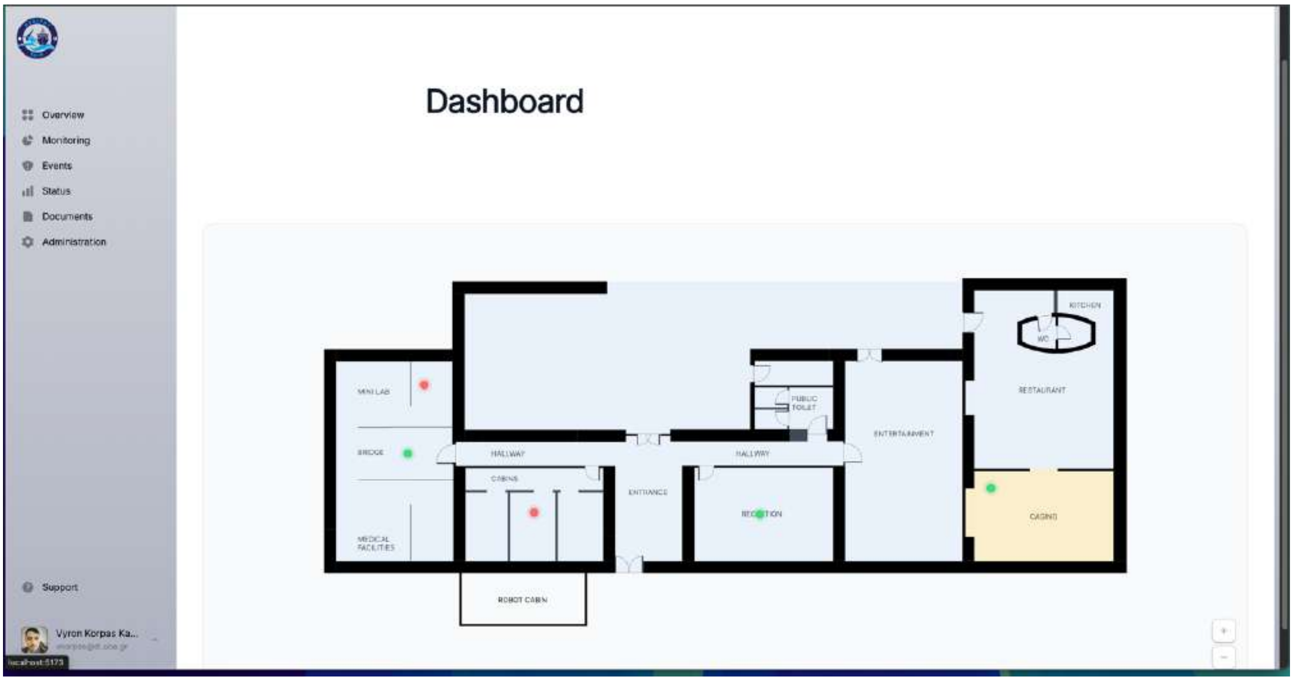

Figure 31 - Collaborative Digital Framework – Use case of the Pilot testing facility

3.10.2 Pilot testing

The Collaborative Digital Framework (CDF) platform was the main platform integrating all the technologies during the pilot testing. All sensors and devices registered were combined with their location in the pilot space. All the resources were monitored in real time during experiments.

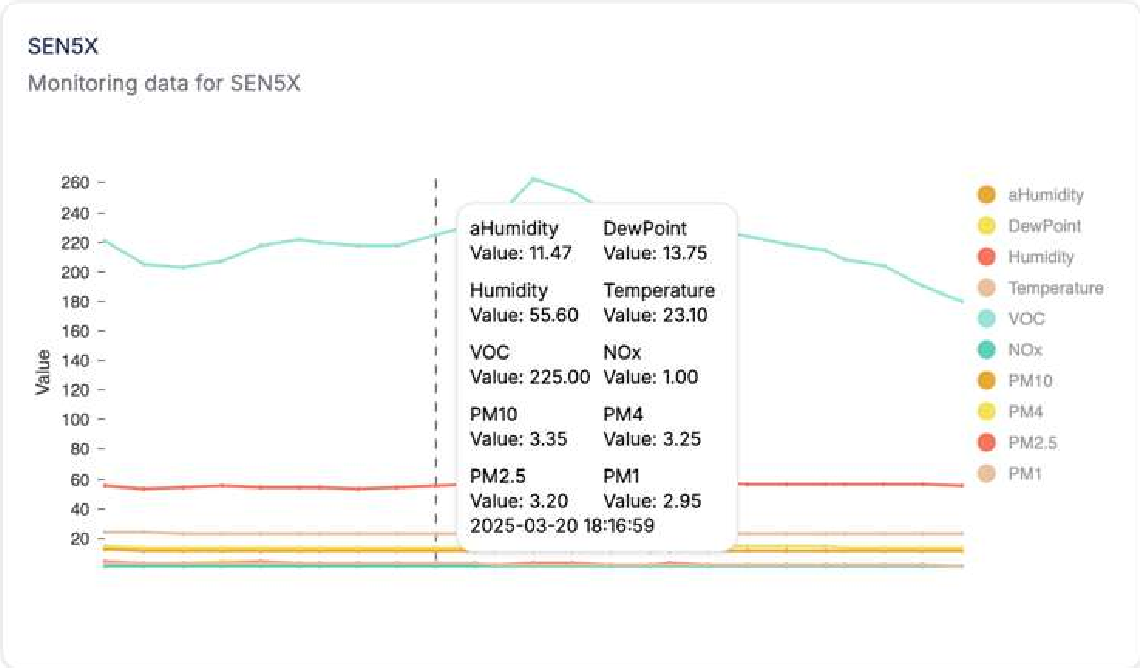

Figure 32 - Resource monitoring in CDF environment

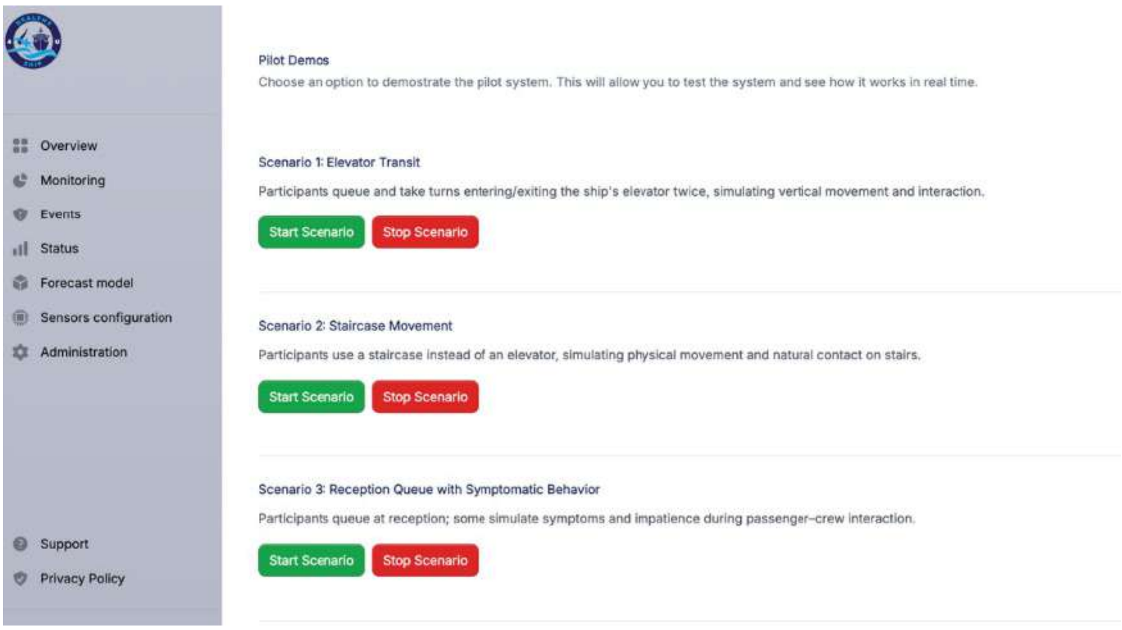

Figure 33 - Pilot Demos execution environment

3.10.3 Key results and discussion

The CDF platform was validated across all demonstration scenarios (Table 3). The assessment was complemented by a structured questionnaire that captured user perceptions. The key findings from this process are available in Appendix 2.

Half of the respondents were very satisfied with the design, while the other half were satisfied, indicating a strong baseline of approval. The layout was described as intuitive by the 62.5% of users, with the remaining 37.5% finding it somewhat intuitive. This suggests that while the interface is generally user-friendly, there may be room for minor improvements in usability. Importantly, all users agreed that the main features are easily accessible from the dashboard, and the clarity of icons and buttons was rated highly, with 75% finding them very clear. The colour coding used for disease risk levels and alerts was also well-received, with no users reporting difficulty in interpreting visual elements, an essential aspect for quick decision-making under critical conditions.

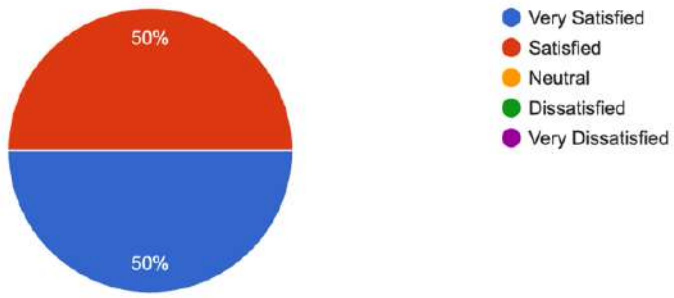

Figure 34 - User satisfaction

The user majority (62.5%) found the software very easy to learn, and 75% reported becoming comfortable with it in under an hour. Half of the respondents could use the software independently, while the other half required only minimal assistance, indicating that onboarding is relatively smooth. Performance consistency was rated as mostly consistent (62.5%) or very consistent (37.5%). Notably, no users reported frequent crashes or errors, with 62.5% experiencing no issues at all and the rest only rare occurrences, demonstrating a high level of reliability.

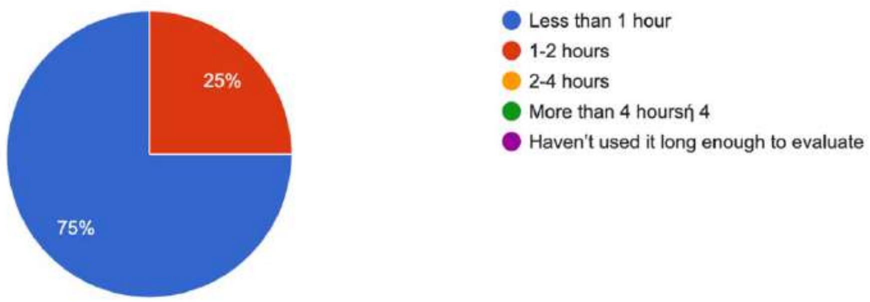

Figure 35 - Time needed to feel comfortable using the CDF software

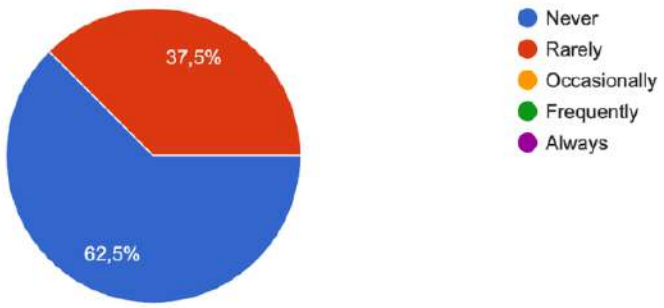

Figure 36 - Incidence of software crashes or errors during use

Efficiency is a standout strength of the CDF software. All users indicated they could use it daily onboard, underscoring its practicality and relevance in operational settings. When compared to manual reporting, which for 50% of users takes over 20 minutes, the software clearly offers a significant time-saving advantage. Half of the respondents rated it as very efficient in supporting disease detection and reporting, and the other half as mostly efficient. Overall satisfaction was high, with 75% very satisfied and 25% satisfied. Most notably, 100% of users stated they would recommend the software to others, a strong endorsement of its value and effectiveness.

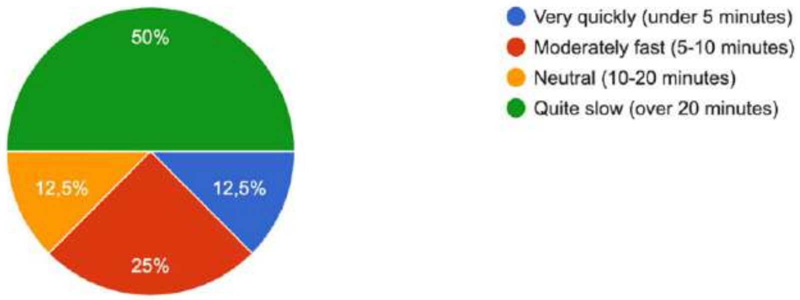

Figure 37 - Manual reporting time without CDF software

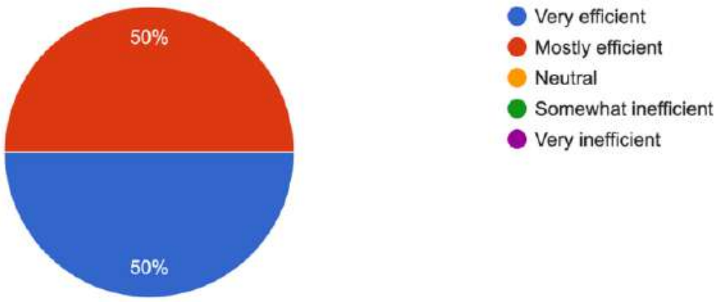

Figure 38 - Perceived efficiency of the CDF software in supporting disease detection and reporting onboard ship, based on user responses

Comparison to the existing protocols/ship equipment

Unlike traditional shipboard health and safety protocols that rely heavily on manual data entry, isolated equipment systems, and delayed reporting, the Collaborative Digital Framework (CDF) introduces an integrated, real-time, and AI-augmented approach to incident management. Existing maritime systems typically operate in silos—environmental sensors, health records, passenger logs, and incident reports are often stored in disparate formats, making cross-analysis and immediate response difficult. In contrast, the CDF platform consolidates all data sources, including software-driven models (passenger behaviour, biomedical analytics, risk forecasts) and physical inputs (onboard sensors, user feedback), into a single cohesive platform. This holistic architecture allows for continuous situational awareness and intelligent decision-making.

Furthermore, while conventional ship dashboards may offer static monitoring tools or delayed updates, the CDF platform's real-time data streaming and advanced dashboard features empower operators to proactively respond to health-related incidents. Integrated data validation mechanisms and privacy-preserving protocols ensure that data integrity and passenger confidentiality are preserved—an area where legacy systems often fall short. By offering predictive analytics and scenario-based risk assessments, the CDF platform represents a significant leap forward from rule-based ship safety procedures, marking a transition toward data-driven, collaborative maritime health management.

Challenges and future development

The CDF platform shows considerable improvement in using data analytics for health management on cruise ships, yet several challenges persist. The main challenge in interoperability exists because legacy maritime systems and equipment need to match current standards and operate in connected digital systems. The systems were built without connectivity features and data exchange capabilities making it hard to achieve seamless interfaces. The process of connecting these systems requires both innovative technical solutions and maritime safety regulation compliance to maintain data integrity and operational stability.

The human factors dimension creates additional difficulties in this system. The success of the CDF platform depends on both technological robustness and its ability to assist ship operators and medical staff and crew members during decision-making activities. The successful implementation of the CDF platform depends on creating simple interfaces and avoiding overload of information and providing proper training to build user trust and increase adoption rates. Data governance alongside regulatory compliance and liability concerns continue to be open challenges when new AI-based functionalities operate in sensitive health-related environments.

The CDF platform's upcoming development strategy contains significant plans for advancement. The platform will achieve predictive analytics accuracy through generative AI and digital twin technologies which will also enable real-time outbreak simulations and passenger behavior predictions under varied environmental and operational conditions. Such capabilities would transform the platform from a primarily reactive tool into a proactive and anticipatory decision-support system. The platform shows potential to expand its functionality into new industries including cruise ships. The CDF architecture and data models could be modified to support freight shipping operations and offshore installations and smart port ecosystems because these domains face similar monitoring needs and predictive risk challenges and response coordination demands. The solution would experience expanded market reach and greater impact through its ability to serve multiple maritime sectors.

Security measures and privacy protection should always take priority during development activities. The growing dependence on cloud services and distributed AI models alongside sensitive passenger health data requires the implementation of enhanced end-to-end security frameworks which should align with the EU AI Act and IMO maritime cybersecurity guidelines for maintaining compliance and user trust. The CDF platform will need ongoing international cooperation between maritime authorities and health organizations and standardization bodies to achieve long-term sustainability and worldwide adoption. The platform's credibility will improve through collaboration to establish data exchange protocols and AI governance practices and evaluation benchmarks which will also guide the digital transformation of the maritime sector.

3.11 StreamHandler

3.11.1 Technology overview

Streamhandler is a distributed, modular data ingestion and processing platform based on Apache Kafka [48]. In the context of HS4U, it has been designed and configured to ensure secure, scalable, and fault-tolerant collection and distribution of real-time sensor and system data, enabling interactions within the HS4U's CDF.

Its architecture comprises of the following:

- A Kafka cluster deployed in Kubernetes [49], with multiple brokers configured in KRaft mode (ZooKeeper-less), offering high availability and horizontal scalability.
- Integration components, such as Kafka Connect for interfacing with IoT sensors, databases, and legacy systems.
- REST-based interaction via Kafka Bridge.
- User-facing monitoring interfaces (Kafka UI) to track data flows and manage configurations.

During the project, StreamHandler has been provisioned on Hetzner Cloud [50], infrastructure within the EU premises. However, the platform can be fully portable: its containerized deployment can be replicated on dedicated servers onboard any ship or within other edge data centres. This enables consistent operation across cloud-based pilots and real-world ship environments, provided that suitable resources (virtualization or bare-metal Kubernetes nodes) are available. For more details regarding StreamHandler, its design and features, reference is made to the deliverable D4.1 [42].

3.11.2 Pilots testing

In the pilot demo space, StreamHandler served as the backbone of the real-time data pipeline connecting the robot-cabin sensors, simulated ship equipment, and the CDF services, as illustrated in Figure 39.

Deployment highlights:

- StreamHandler was deployed in a secure Kubernetes cluster configured to mimic a production environment.
- Message Queuing Telemetry Transport (MQTT) connectors and clients ingested telemetry from the GCM multi-sensor units installed in the robot cabin and the other simulated ship compartments (ambient temperature, occupancy, noise level, indoor environmental conditions).
- Kafka producers ingested passenger temperature measurements coming from thermal cameras located in the entrance and the cabins.
- Kafka clients produced periodic status and virus event detection messages from the VDS.
- Kafka Streams jobs processed data streams to detect simulated abnormal conditions (e.g., high passenger temperature above specific thresholds) and send corresponding notifications.

- Data was forwarded to monitoring components for permanent storage in databases, visualization in dashboards of the CDF UI and the usage by decision making components (e.g., Risk Assessment module).
- Actuation commands initiated by the simulated crew via the CDF UI were sent to the passenger dashboards and the embarkation check-in kiosk, including information for onscreen notifications and visual signals via smart lamps.
- The monitoring tool Kafka UI was used by the platform administrators (The technical team of INTRA project partner) to oversee ingestion status, connector health, and message flow in real time.

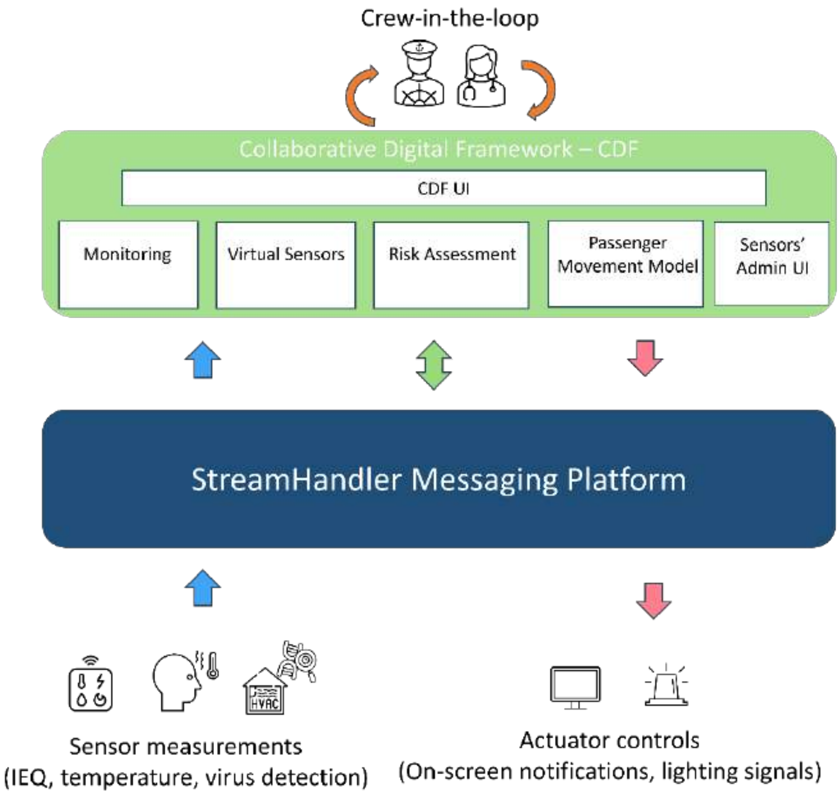

Figure 39:StreamHandler's role in HS4U and the pilot testing

The pilot involved scenarios where trained crew and other individuals acting as passengers enacted events requiring the system to process live sensor data and trigger CDF outputs. Testing validated the end-to-end flow from IoT devices to analytics and response workflows. For more details regarding the data flows and the interactions between all system components, see deliverable D4.1 [42].

3.11.3 Key results and discussion

The pilot successfully validated the feasibility and stability of StreamHandler in supporting continuous data ingestion and processing in realistic setups. While the core pilot experiments (Table 3) lasted three days, there were extended integration and stress testing sessions that spanned multiple weeks before the pilots.

Key results are summarized as follows:

- Data latency: For most kinds of payloads, the message delivery from ingestion to storage averaged under 300ms.
- Resilience: No data loss or downtime was recorded, demonstrating successful continuous operation of brokers, clients and connectors.
- Scalability: The system sustained concurrent ingestion from multiple topics and sensor streams.
- Portability: Tests confirmed that the containerized services could be redeployed with minimal configuration changes on other Kubernetes environments, including on-premises servers that could be installed aboard ships.

The Monitoring Streamhandler health status was achieved via a combination of monitoring tools that provided clear observability and simplified issue diagnosis. A Hetzner Console (Figure 40) was used for the visualization of various performance metrics related to the health of servers running the Kafka brokers and the connectors/clients (e.g., CPU usage, disk input/output, networking). The Kafka UI provided real-time monitoring of Kafka topics including the number of messages sent to each topic and their size (Figure 41) and inspection of the exchanged messages (Figure 42).

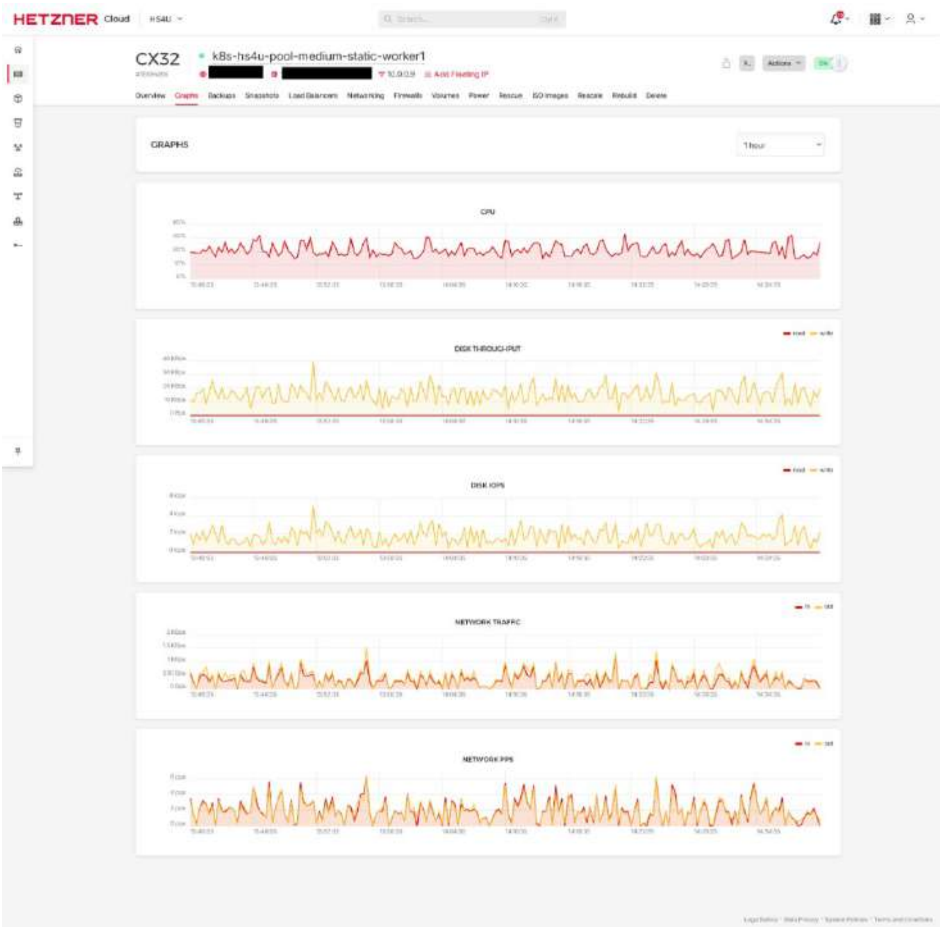

Figure 40: Hetzner Console graphs for monitoring resource usage of servers

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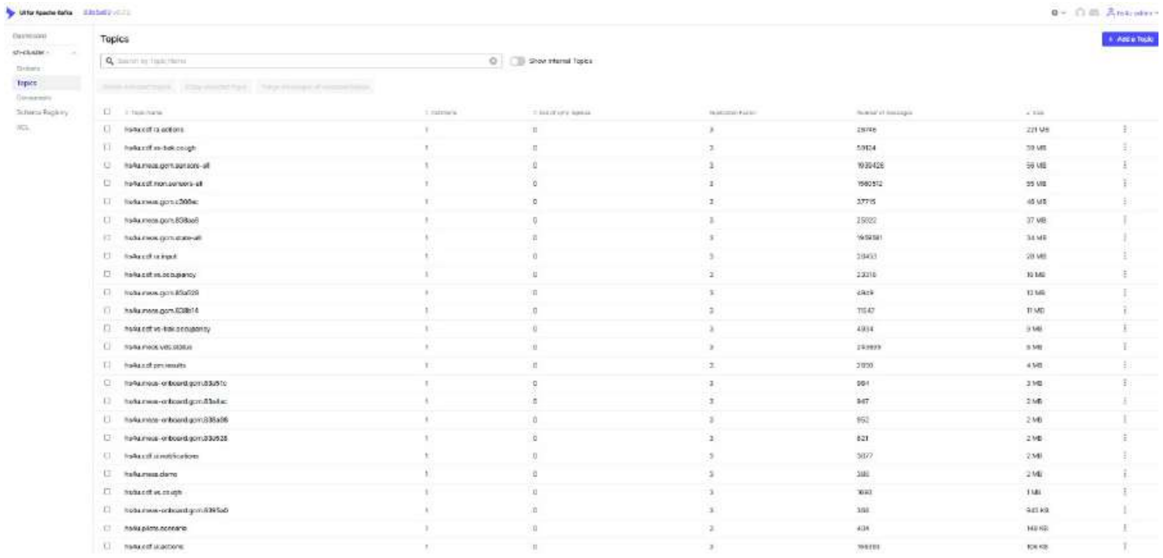

Figure 41: Kafka UI topics menu

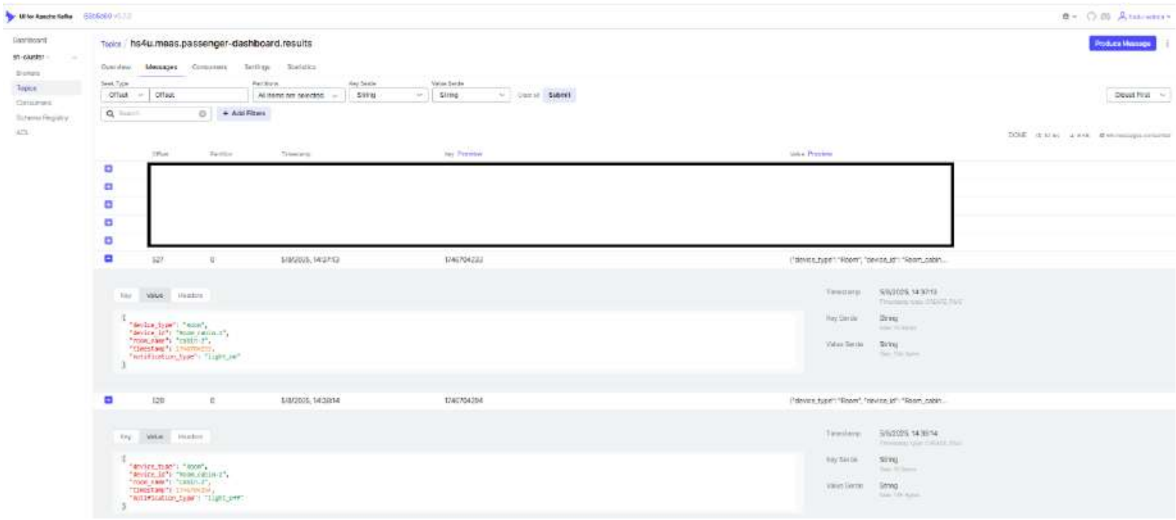

Figure 42: Kafka UI messages inspection

In relation to the additional KPIs that were defined by the HS4U consortium within the T5.1 [30], the StreamHandler was indirectly related to the following ones since it serves as the message bus that enables the respective interactions.

- The number of alerts and messages to the CDF system supervisor for airborne diseases. Throughout the pilot testing VDS periodically transmitted virus detection events that were forwarded to the CDF user interface (Section 3.10).
- Early symptoms detections. Instrumented coughing events during the pilot testing were ingested to the RA module and led to the corresponding notifications for the onboard personnel via the CDF user interface.

These results validate StreamHandler's readiness for operational use in maritime contexts.

Compared to traditional ship monitoring systems, which often rely on isolated data loggers or proprietary control systems, the StreamHandler introduces an open, event-driven architecture that enables standardized integration of heterogeneous sensors and IT systems. It supports near real-time processing pipelines rather than periodic polling or batch transfers, and includes built-in encryption and access control across all data flows. Additionally, it offers transparent scaling without the need for specialized vendor hardware. This approach aligns with modern digital ship initiatives but represents a significant evolution beyond legacy protocols such as NMEA (National Marine Electronics Association) or simple SCADA (Supervisory Control and Data Acquisition) telemetry.

However, several challenges have also been encountered. Training was necessary for other HS4U project partners, who were given guidance and support to incorporate Kafka into the business logic of their software components. Network configuration required fine-tuning ingress and encryption settings to support low-latency and secure data ingestion over potentially unreliable connections. While cloud resources offered flexibility, replicating realistic onboard resource constraints (CPU, storage) will require further investigation.

Looking ahead, future directions involve deploying StreamHandler on dedicated shipboard servers or edge clusters, implementing automated scaling policies adapted to the constrained compute environments typical to ships, enhancing connectors to ensure compatibility with legacy maritime protocols, and refining user interface tools for non-expert operators.

4. RECOMMENDATIONS

4.1 Development of Goal-Based standards

The Goal-Based Standards (GBS) framework serves as the foundation for any regulatory development at IMO level and as such, it can also be used for establishing more detailed requirements related to health protection of crew and passengers against communicable diseases onboard ships. This approach entails the formulation of broad goals, functional requirements to achieve those goals, and verification processes to ensure compliance. This section aims to outline the fundamental philosophy of applying GBS within the risk assessment process, as the preferred path for compliance with safety requirements which is typically applied for all alternative designs, novel concepts, and generally new technologies.

The GBS framework consists of five major components (see Figure 43), namely (1) Tier I - Goals; (2) Tier II - Functional Requirements; (3) Tier III - Verification of conformity; (4) Tier IV - Regulations and Class requirements; (5) Tier V - Industry standards and practices. Alternatives, new technologies, and novel concepts may be accepted if designers, shipyards, owners, equipment manufacturers, or other stakeholders can demonstrate compliance with the Tier I Goals and Tier II Functional Requirements, during Tier III Verification of Conformity. When a goal-based approach is used as the basis for compliance with Administration and Coastal State requirements, the Administration is to be contacted, either directly or through a Classification Society, to obtain an understanding as to the extent to which the Administration is prepared to consider alternatives to such requirements. The following sections describe items of relevance to GBS Tiers.

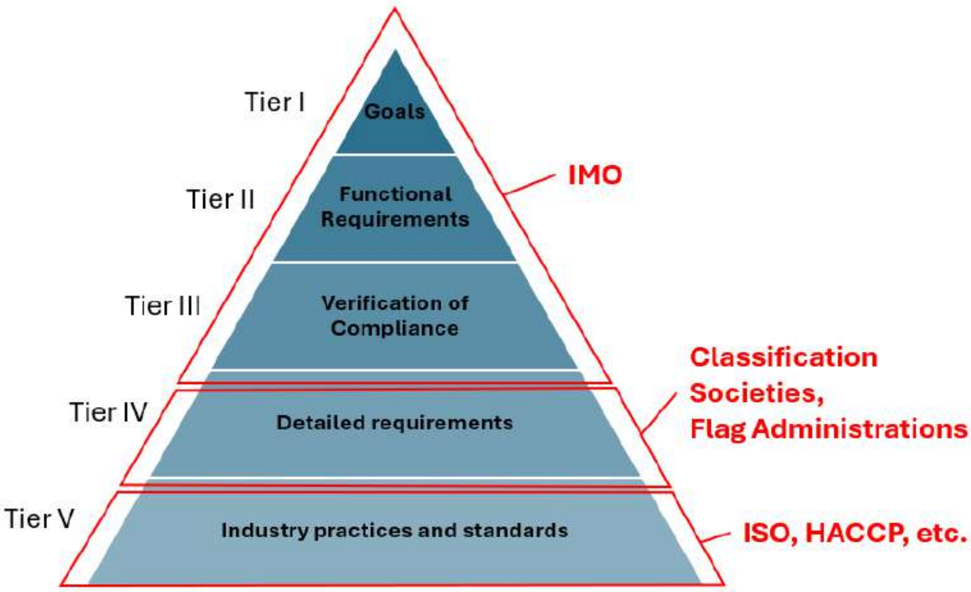

Figure 43. Tiers of the IMO's Goal Based Standards framework

4.2 Goals

A goal should address the issues of concern and reflect the required level of safety. In alignment with the World Health Organization’s overarching objective as outlined in the International Health Regulations (IHR) [11], namely:

> *“...to prevent, protect against, control and provide a public health response to the international spread of disease in ways that are commensurate with and restricted to public health risks, and which avoid unnecessary interference with international traffic and trade*”

a more tailored goal applicable to the maritime sector can be formulated as follows:

> *“Ensure the health protection of cruise ship passengers and crew against the risk of transmission of communicable infectious diseases throughout the ship voyage.”*

4.3 Functional requirements

Functional requirements provide the criteria to be complied with, to meet the goals. Once a goal has been set, functional requirements can be developed. The functional requirements should cover all areas necessary to meet the goals and to address relevant hazards.

In the context of mitigating the spread of communicable infectious disease in the maritime sector, functional requirements can fall under the three key public health pillars, namely prevention, screening and diagnosis, and containment. These requirements can be additionally organized chronologically according to the three phases of a ship voyage: (a) prior to or upon embarkation, (b) onboard the ship, and (c) prior to or upon disembarkation. The scope of work under HS4U is to focus on activities conducted onboard ships. As such, the analysis concentrates on phase (b), excluding measures implemented at the port’s environmental setting during embarkation or disembarkation of ship passengers.

To achieve the stated goal, the applicable functional requirements can be articulated as follows:

- **Prevention.** Ships should be designed, operated and maintained to support effective prevention and control measures against the spread of communicable diseases.
- **Detection.** Ships should have capabilities to detect and respond to potential outbreaks of communicable diseases effectively.
- **Containment.** Ships should be equipped with medical facilities and staff to diagnose, treat and isolate individuals with suspected infectious diseases.
- **Training.** All individuals onboard, including both crew and passengers, should be adequately informed of the risks associated with the transmission of infectious diseases and the importance of the applicable preventive, detection and containment measures.
- **Communication.** Ships should maintain coordination protocols with public health authorities on diseases management and reporting.

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4.3.1 Hazards

To ensure compliance with the above functional requirements, it is essential to identify first relevant hazards. This enables the implementation of effective and appropriate measures or safeguards. Communicable diseases encompass a diverse array of pathogenic agents, including viruses, bacteria, fungi, and parasites, which can manifest through a variety of clinical symptoms and are transmitted via multiple routes. Communicable diseases can be broadly categorized as follows:

- Airborne transmission, which involves the spread of pathogens through aerosols or respiratory droplets.
- Physical contact transmission, where infection occurs through person-to-person interaction,
- Food or water transmission, leading to ingestion of harmful pathogens,
- Vector-borne transmission, involving carriers such as insects or rodents,
- Transmission via contact with contaminated surfaces, where pathogens are transferred via inanimate objects.

While all the modes of transmission and corresponding hazards are relevant within a ship environment, not all of them necessarily warrant equal prioritization. In the maritime industry, the identification and prioritization of hazards is typically carried out through structured risk assessment processes. This process generally includes the following steps:

- **Hazard Identification.** Recognizing potential hazardous sources within a ship's specific environment and operations.
- **Risk Estimation.** Assessing the likelihood and potential consequences of each identified hazard using qualitative or quantitative data.
- **Risk Evaluation**. Comparing the estimated risks against established criteria to determine their level of significance and acceptability.

4.3.2 Hazard identification

Focusing on the passenger vessel and cruise ship sectors and considering the initial step of the risk assessment process (i.e., hazard identification), findings from the literature review [10], indicate that communicable pathogens are associated with:

- Respiratory infections (e.g., SARS-CoV-2 / COVID-19, Influenza, Rubella).
- Gastrointestinal infections (e.g., Noroviral infections, Enterotoxigenic Escherichia coli, Salmonella gastroenteritis).

While the epidemiological characteristics of the various pathogens vary significantly, including their means of transmission and caused symptoms, the HS4U project focused on two primary categories namely, airborne and surface/water-transmitted diseases.

Specifically, SARS-CoV-2 (COVID-19) has been nominated as a representative case for airborne-transmitted diseases causing respiratory infections, while the Norovirus has been considered indicative of pathogens transmitted via contaminated surfaces and water, causing gastrointestinal infections. Using these two pathogens as test cases, a series of representative scenarios involving

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cruise ship environments and operations were assessed [31], to identify specific shipboard activities that may contribute to high-risk public health events.

Based on the review of typical architectural configurations of large cruise ships and a qualitative screening of onboard areas and operations, guided by selected risk factors, a preliminary ranking of health risks across various spaces was conducted [44] and is summarized in Table . The risk factors considered for the assessment are:

- Typical air exchange rates for the ventilation system,
- Frequency of contact with potentially contaminated surfaces or objects,
- Population density, congestion levels,
- Effectiveness and frequency of cleaning or sanitization,
- Prevalent social behaviours,
- Likelihood of contact with individuals who are symptomatic or suspected to be ill.

This analysis highlighted that spaces with high population density per unit area, such as bars, casinos, elevators, main entrance halls, or those where individuals come into direct or indirect contact due to the nature of activities taking place, such as restaurants and restrooms, require increased attention and prioritization.

Figure 44: Empirical risk levels of ship compartments based on low, medium and high exposure risk.

Table 17.Empirical risk levels of ship compartments based on low, medium and high exposure risk (Source: [44])

Classification	Characteristics	Limited ventilation and air exchange	Direct contact with infected surfaces and objects	Possible overcrowding/insufficient capacity	Direct contact between passengers and crew	Difficult cleaning/sanitizing of surfaces/objects	High density of persons (social distancing issues)	Congestions at entrance/exit	No secondary entrance/exit	Direct contact with suspected or positive cases	Example
Low exposure risk	Areas with no direct contacts with persons, or where contacts are limited in time or to the members of a family unit; Areas with no direct contact with a suspect or positive case.	✓	✓	✓	✗	✗	✗	✗	✗	✗	Corridors, Stairs, Cabins
Medium exposure risk	Areas with no direct contact with a suspect or positive case; Areas used as an aggregation point by passengers/crew; Areas where social distancing cannot be kept or PPE cannot be used for limited periods due to proximity; Internal spaces with limited air exchange capability.	✓	✓	✓	✓	✓	✓	✓	✓	✗	Restaurants, Bars, Cinemas, Theatres, Casinos, Elevators,
High exposure risk	Areas with direct contact with a suspect or positive case.	✓	✓	✓	✓	✓	✗	✗	✗	✓	Medical zone, Quarantine areas

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4.3.3 Risk Estimation

Risk estimation, within the broader framework of risk assessment, refers to the process of evaluating the likelihood of a specific hazardous event occurring and the magnitude of its potential consequences. It is typically expressed as a function:

$$Risk = Likelihood\ x\ Severity$$

This means that even if an event is unlikely to occur, it may still represent a significant risk if the consequences are severe. Conversely, a highly likely event with minimal impact may also warrant attention. In practical terms, risk estimation involves gathering and analysing data to assign qualitative or quantitative values to both the probability of occurrence and the severity of outcomes. This step is essential for prioritizing risks and informing decision-making.

However, estimating the likelihood and potential impact of a public health event appears to be particularly difficult when judging solely on qualitative factors, such as the characteristics of the space and the nature of the activities taking place within it. Even assuming the presence of a pathogenic agent within a closed system, such as the environment of a ship at a given point in time, the quantification of its transmission dynamics remains a complex task. This complexity arises from the interplay of numerous parameters, which can be broadly categorized into three main domains:

1. Epidemiological characteristics of the disease, including but not limited to:
    - Duration of exposure
    - Basic reproduction number (R_0)
    - Incubation and infectious periods
    - Morbidity and mortality rates
    - Mode of transmission (e.g., airborne, droplet, contact)
    - Population susceptibility and immunity levels
2. Environmental conditions, such as:
    - Ambient temperature
    - Relative humidity
    - Ventilation efficiency and air exchange rates
    - Surface contamination and material properties
    - Spatial configuration and crowd density
3. Social and behavioural Factors, including:
    - Adherence to social distancing measures
    - Hygiene practices (e.g., handwashing, mask usage)
    - Nature, frequency, and intensity of interpersonal interactions
    - Duration and type of activities conducted in the space
    - Communication and compliance with public health guidance

In this context, the HS4U project has developed an innovative risk assessment framework that quantitatively evaluates the likelihood of infectious disease outbreaks on board ships (Section 3.9). This framework integrates real-time data from i) physical sensors, ii) biomedical resources for specific diseases, and iii) simulation-based modelling outputs to deliver dynamic and evidence-based risk estimations.

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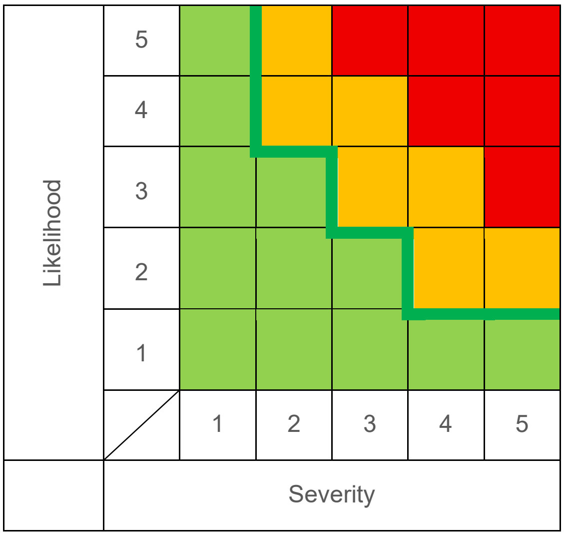
At the core of this tool, lies a fuzzy-logic inference system which consumes the suite of data sources and outputs a quantitative risk score with an associated confidence level [47]. When confidence in the initial risk estimate is low, the system triggers a simulation module to refine the assessment.

4.3.4 Risk Evaluation

The ALARP (As Low As Reasonably Practicable) principle typically applies to risk management strategies. In this context, criteria for risk acceptability are established by project stakeholders who agree on the point at which the benefits of further risk reduction are outweighed by the increasing costs of mitigation.

Figure 45: The ALARP Principle

The risk matrix used in Task 5.1 of the HS4U project is presented in Figure 46 & Figure 47. In this matrix, the orange and green zones represent risks that are considered tolerable, since they fall below the threshold level that is considered ALARP. Conversely, the red-shaded area indicates high and unacceptable risk levels, which necessitate mitigation through design modifications or technological upgrades.



Acceptable	1-6	No additional controls are required. Risk is already “As Low As Reasonably Practicable” (ALARP)
Tolerable	8-12	Efforts are required to reduce risk to the ALARP level. Additional safeguards are required.
Intolerable	15-25	Risk is intolerable. Control measures should apply to reduce risk. If reduction is not possible, the activity shall be prohibited or an approval by the company is required.

Figure 46: Risk Matrix adopted in HS4U

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Likelihood	Rank	Description	
Remote	1	Might happen once in lifetime	
Occasional	2	Might occur or occurs every 10-20 years	
Likely	3	Might occur or occurs every 1-10 years	
Probable	4	Might occur or occurs once a year	
Certain	5	Might occur or occurs once every 6 months	
Severity	**Rank**	**Description**	
Negligible	1	Safety: Minor injury not requiring first aid	Cost: less than 10,000$
Minor	2	Safety: Minor injury requiring first aid treatment onboard	Cost: 10,001$ –100,000$
Significant	3	Safety: Injury requiring hospitalization	Cost: 100,001$ – 1 million $
Critical	4	Safety: Single death or permanent disability	Cost: 1 million $ – 25 million $US
Catastrophic	5	Safety: Multiple deaths	Cost: More than 25 million $

Figure 47: Likelihood and Severity levels

4.4 Measures to satisfy functional requirements

Recommendations typically fall under three public health pillars: i) prevention, ii) screening and diagnosis, iii) mitigation and containment, and they may also be grouped by chronological order in one of the three phases of cruise travel, namely (a) before or upon embarkation, (b) on board the ship and (c) prior to or upon disembarkation. Deliverable D2.1 [10], presents a comprehensive overview of all documented measures, compiled in accordance with the applicable guidelines from various public health bodies. A summary of these measures is provided below.

Prevention measures aim to reduce the likelihood of disease transmission before it occurs. Key strategies include:

- Promotion of vaccination to build immunity across populations
- Behavioural practices such as enhanced hand hygiene, cough and sneezing etiquette, and the use of medical masks by individuals.
- Environmental controls such as increased disinfection, touchless interactions, physical barriers, improved ventilation and capacity limitations in enclosed spaces to prevent overcrowding, further reduce transmission risks
- Review of travel history, temperature screening and close contact tracing add layers of proactive monitoring.

Screening and diagnosis measures focus on identifying infected individuals promptly and accurately. This pillar includes:

- Use of medical questionnaires to assess risk factors and symptoms, alongside routine screening and rapid testing to detect cases early.
- Expanding onboard testing and clinical diagnosis capabilities.
- Procedural measures for collaboration with external, shore-based testing facilities.

Containment and mitigation strategies are activated once a case is suspected or confirmed. This pillar includes:

- Quarantine and isolation of patients, preferably in single cabins, to minimize exposure.
- Use of strict disinfection and waste management protocols to eliminate environmental contamination.
- Wearing of PPE during interactions.
- Close contacts tracing followed by monitoring of their health to ensure early detection of secondary cases.
- Procedural measures for collaboration with external stakeholders such as public health agencies and authorities.

Despite the implementation of measures across the three public health pillars, several gaps persist that hinder the effective management of disease outbreaks onboard ships.

<u>In the prevention domain</u>

Measures based on behavioural practices, such as hand hygiene, mask usage, and cough and sneezing etiquette, play a critical role in disease prevention but are inherently limited by individual compliance and cultural variability. They rely on personal responsibility and willingness to adhere to guidelines, which can vary across different passenger demographics. Moreover, consistent enforcement and monitoring of such behaviours are challenging, especially in crowded and dynamic environments like cruise ships. As a result, behavioural measures cannot be considered as standalone solutions for outbreak prevention and control, making it essential to complement them with technology-driven solutions.

According to the WHO IHR, invasive medical procedures, including vaccination or other prophylaxis, must not be enforced as a condition of entry for international travelers unless such measures are justified by a public health risk and deemed necessary. While vaccination can serve as a valuable risk assessment parameter, it cannot be considered as an enforceable preventive measure, particularly in the context of cruise travel. Cruise ship passengers are not only travelers but also customers who invest in their holidays, and any health protocols imposed must be proportionate to the risk levels and justified.

In contrast, environmental control measures offer a more reliable and scalable approach to onboard disease prevention. Within the HS4U project, particular emphasis was placed on the disinfection of surfaces and indoor air onboard cruise ships, recognizing these as critical areas for disease transmission. Table presents the interventions proposed by HS4U within the domain of disease prevention.

Table 18: HS4U proposed interventions within the domain of disease prevention.

Antimicrobial surface coatings	Regular cleaning and disinfection of high-touch surfaces, such as handrails, elevator buttons, door handles, fabrics, are critical components of disease prevention policies onboard cruise ships. Such tasks are carried out by crew members, with shipping companies investing substantial resources to uphold high hygiene standards. To further enhance surface sanitation efforts, especially on hard-to-clean or frequently touched areas, the use of antimicrobial coatings with active disinfection properties and long-lasting effects, such as those developed by CNT-lab within the HS4U project, could offer a valuable complementary solution. These coatings can provide continuous protection between cleaning cycles, reinforcing onboard hygiene protocols and reducing the risk of disease transmission.
Smart HVAC systems	Heating, ventilation, and air conditioning (HVAC) systems on board ships play a vital role in maintaining a comfortable and healthy indoor environment. To minimize energy consumption, these systems typically operate under air recirculation modes, with recirculated air ranging from 30% to 70%, depending on the system's design and operational requirements. Recirculation is generally applied in areas where precise temperature and humidity control is essential and where the presence of contaminants is minimal such as the passenger accommodation areas. However, during disease outbreaks, the ability to control HVAC systems in a way that isolates potentially infected compartments and minimizes air recirculation becomes critical. Such control is essential for mitigating the risk of uncontrolled transmission of infectious diseases and ensuring the safety of passengers and crew. Although the inspection of HVAC systems for confirming their proper function is part of routine shipboard checks (e.g. Ship Sanitation Certificate, Port State Control surveys), their role in harbouring and transmitting pathogens remains unaddressed. While ventilation systems are designed with filters, isolation mechanisms, and drainage arrangements to uphold hygiene standards, the thorough cleaning of their internal components remains an operational challenge. Beyond the implementation of structured maintenance activities by ship management, which should be comprehensively addressed within the Ship's Management System (SMS), regular disinfection is a key measure in mitigating the transmission of viruses and respiratory illnesses. Technological solutions, such as combining the VDS sensor, which actively monitors the presence of pathogens within the ventilation system, with the Probiotic Emitter, which can automatically disinfect the HVAC system upon detection and without requiring crew intervention, offer a promising and efficient approach to improving onboard health safety.

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In the screening and diagnosis domain

Among the three public health pillars, screening and diagnosis appears to be the most constrained in its practical application within the maritime industry. Current public health guidelines emphasize individual screening through medical questionnaires, rapid testing, and clinical assessments. This approach benefits from standardized procedures, making it widely applicable and relatively straightforward to implement. However, onboard cruise ships, the infrastructure and availability of medical personnel are often limited, making extensive and timely screening difficult to implement. Moreover, preventive clinical screening may be considered invasive by passengers, especially when not clearly justified by the prevailing health conditions.

Building on these limitations, the HS4U introduced technological interventions in the field of community-level surveillance that offer a reliable and non-intrusive alternative. These systems enable early detection of communicable diseases without relying on individual symptom tracking or clinical examinations, providing timely insights into onboard health conditions. Table presents the interventions proposed by HS4U within the domain of community-level disease surveillance.

Table 19: HS4U proposed interventions within the domain of community-level disease surveillance.

Wastewater analysis for pathogens	During the SARS-CoV-2 pandemic, extensive wastewater analytics conducted in municipalities revealed a strong correlation between viral concentrations in sewage and subsequent hospitalization rates, often detecting the virus up to seven days before individuals exhibited symptoms [51]. Building on this evidence, wastewater sampling has gained recognition as a reliable method for early detection and surveillance of viral outbreaks within populations. Applying this approach to large cruise ships enables timely, data-driven insights into onboard health conditions. The use of automated technologies, such as the RWO’s wastewater sampling device, supports this capability by eliminating the biological risks of manual handling and ensuring consistent, unattended data collection.
Airborne pathogen detection through HVAC systems	Analysing ventilation air for disease surveillance, in a manner similar to wastewater analytics, presents a promising method to public health monitoring. This strategy is particularly well-suited to large cruise ships and passenger vessels, which combine enclosed environments with high population densities, conditions that can accelerate the transmission of airborne diseases. Within the HS4U project, this concept was advanced through the development of the Viral Detection Sensor (VDS), a pathogen detection system designed for real-time, continuous monitoring. The VDS collects air samples directly from a ship’s HVAC system and analyses them for the presence of genetic material (DNA/RNA) from known airborne pathogens. The system enables early detection of health threats, often before symptoms become widespread, allowing for quicker containment and mitigation measures onboard.

In the disease outbreak mitigation domain

The set of containment and mitigation measures also encounter several operational challenges that reduce their effectiveness in controlling disease outbreaks onboard ships. A key issue is the reliance of the safety protocols upon manual collection and analysis of health-related data, which can be both error-prone and resource-intensive, especially when dealing with large populations. The reliance on manual processes often results in delays and inaccuracies in assessing the evolving risk of an outbreak, which is inherently a dynamic and time-sensitive situation. Human factors, such as misjudgements, misconceptions, or lack of training, can further compromise the quality and speed of decision-making. Additionally, miscommunication among crew members, medical personnel, and external stakeholders often hinders the coordinated execution of critical mitigation activities, such as patient tracing and isolation.

To address these operational limitations, the HS4U project has developed a suite of technological solutions aimed at automating key aspects of disease outbreak management onboard ships. These solutions focus on the real-time collection and analysis of health-related data, enabling faster and more accurate risk assessments and improve situational awareness. Table outlines the proposed HS4U interventions within the domain of disease outbreak mitigation, highlighting how these innovations directly respond to the challenges identified in current practices.

Table 20: HS4U proposed interventions within the domain of disease outbreak mitigation.

Passenger Dashboard & Check-in point devices	Maintaining manual medical logs for symptoms of communicable diseases, such as fever or coughing, is a time-consuming process that is typically applied during patient isolation and relies heavily on self-reporting. Automated detection methods and technological solutions, such as the UNP dashboard, can efficiently and rapidly collect data from a large portion of the shipboard population. These tools can significantly support the early identification and management of outbreaks, enabling timely and consistent implementation of control measures. Installing such devices in strategic locations, such as high-traffic areas for early detection of suspected cases, and within cabins to monitor the progression of symptoms at an individual level, can further enhance surveillance capabilities.
Communicable Disease Framework (CDF) platform	Effective communication is one of the most challenging aspects of managing a disease outbreak, both on board ships and within other closed communities. Internal communication between potentially affected individuals - whether crew or passengers - and the ship's medical personnel, as well as external communication between ship masters and relevant stakeholders such as competent authorities, is critical for accurately assessing health conditions during an outbreak. Although these communications are currently governed by established procedures outlined in WHO protocols, delays in evaluating the situation from any party involved remain a significant risk. To address this shortcoming, technological solutions such as the Communicable Disease Framework (CDF), developed within the HS4U project, can play a vital role. The CDF enhances the speed and reliability of communication, enabling real-time information exchange and effective decision-making. Its integrated risk assessment module is customized to the

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	specific characteristics of each cruise ship, such as the voyage plan and passenger demographics, and enables dynamic evaluation of disease transmission risks. Complementing this, the passenger behaviour monitoring component offers valuable insights into movement patterns and social interactions that may affect the spread of illness. Together, these features enhance the ability of ship operators and health authorities to respond quickly and effectively, strengthening containment efforts and protecting public health.

5. CONCLUSIONS

Disease outbreaks onboard cruise ships present significant public health risks and operational challenges, often resulting in substantial costs related to evacuation, isolation, and repatriation. Over the past decades, public health organizations have developed and issued a range of manuals and guidelines aimed at establishing standards and recommending best practices for the management of communicable disease outbreaks in the maritime environment. These guidelines are generally structured around three core pillars: i) prevention, ii) screening and diagnosis, and iii) containment and risk mitigation. Central to these efforts is the development of outbreak management plans, supported by systematic risk analysis as a foundation for preparedness. Typically, the implementation of public health procedures onboard begins with event detection, triggered by routine surveillance, crew reporting or passenger self-reporting of symptoms.

Identified weaknesses include the lack of practical tools in the areas of early detection and fast screening of large populations, the human factors involved in the assessment and management of health crisis, as well as the reliance on non-automated protocols which can induce delays during an outbreak. These challenges are further compounded by the limited medical infrastructure and personnel typically available onboard cruise ships. When the number of infected individuals exceeds a small threshold, the capacity to manage the situation effectively becomes severely constrained.

Bridging these gaps, HS4U prioritized the development of technological solutions for automated surveillance and real-time monitoring, overcoming the limitations of manual data collection and analysis. Among the most impactful innovations are community-level pathogen surveillance tools designed for integration with wastewater and air ventilation systems that allow the detection of virus and pathogens onboard. These methods have been favoured over more invasive health monitoring technologies, such as wearable devices or camera-based systems, due to their minimal impact on passenger privacy and comfort.

Furthermore, the CDF platform developed under the HS4U, serves as a powerful for health crisis management onboard ships. By integrating and cross-analyzing environmental data, health records, and passenger information, this software platform enables dynamic, data-driven risk assessments in real-time that go beyond the traditional protocols that rely on symptom-based reporting. This capability not only enhances decision-making processes, but it can also contribute to the refinement of the WHO International Health Regulations (IHR) decision instrument (Annex 2, [11]) by embedding data-driven analytics for a more immediate and accurate understanding of public health threats in maritime settings.

On the prevention front, HS4U project has introduced innovative solutions aimed at enhancing onboard hygiene and reducing the risk of disease transmission. Among these are antimicrobial surface coatings, which provide continuous protection between cleaning cycles, significantly reducing the dependence on individual hygiene practices. Additionally, the probiotic emitter device offers a novel disinfecting mechanism by releasing beneficial microorganisms into the environment, helping to outcompete harmful pathogens on surfaces and in the air.

To validate the performance and operational feasibility of the HS4U technologies, two dedicated testing campaigns were conducted, one onboard an actual cruise ship and another within a controlled, shore-based environment. These trials aimed to assess the effectiveness of each technological solution under realistic and varied operational scenarios. While the technologies have not yet reached full maturity levels, the results obtained across both testing environments were

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promising. In most cases, the systems demonstrated strong potential to enhance public health management, addressing critical gaps in the current maritime health protocols.

Overall, HS4U puts forward a set of well-tested, efficient and integrated public health protection solutions that can significantly enhance safety onboard cruise ships. By addressing critical gaps in current maritime health protocols, the project offers a forward-looking solution aligned with evolving public health needs. The technologies developed under HS4U not only improve operational preparedness but also support the refinement of international health regulations, reinforcing institutional trust in cruise travel across the EU and globally.

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APPENDIX 1: Consolidation of recommendations based on the existing framework, Source: *[10]*

Table 21: Consolidation of recommendations for COVID-19 outbreak – by public health pillar

	ICS (2022)	CDC (2022)	CDC et al. (2022)	ECDC/ EMCA (2021)	HEALTHY GATEWAYS (2020,2022)	WHO (2020)
Prevention						
Before/Upon embarkation						
Assess maximum number of passengers and crew to implement health related safety measures				X	X	
Promote vaccination of crew and passengers before boarding		X	X	X	X	
Relocate all crew to single occupancy cabins			X			
Scan / measure temperature	X	X		X	X	X
Screen for signs &symptoms	X	X		X	X	X
Scan for close contact with case prior to boarding the ship	X	X		X	X	X
Request viral test / present negative test result prior to boarding		X				
Request proof of vaccination status and assess validity before boarding					X	
Advise pre-travel medical consultation					X	

Complete locator card	X			X		
Deny embarkation to those experiencing signs & symptoms	X		X			
Develop an exclusion policy for COVID-19					X	
On board the ship						
Enforce / promote hand hygiene	X	X	X	X	X	X
Discourage hand shaking		X	X			
Ensure access to hand sanitizers		X	X			
Enforce /promote cough etiquette	X	X	X	X	X	X
Wear medical masks (indoors / when interacting with port)	X	X	X	X	X	X
Promote use of PPEs			X	X	X	
Set up physical barriers to avoid crowding		X				
Maintain physical distancing – avoid all non-essential contact	X	X		X	X	X
Maintain physical distancing in gyms and disinfect exercise equipment					X	
Reduce face-to-face interactions between passengers and crew		X		X	X	

Modify meal service to facilitate social distancing		X				
Implement food safety rules					X	
Change restaurant and bar layouts to avoid crowding between parties		X				
Limit seating capacity		X				
Discourage crowded waiting areas		X				
Consider options for passengers to order ahead of time to avoid crowding		X				
Limit elevator capacity and capacity in entertainment venues / activities		X			X	
Increase space between seats and gaming equipment in casinos		X				
Improve ventilation in indoor areas		X		X	X	
Consider adding supplemental air ventilation or air treatment devices		X				
Improve ventilation in casinos		X				
Thoroughly ventilate cabins between cruises					X	
Use outdoor areas, external stairway /escape routes and walkways	X	X			X	

Provide and encourage outdoor dining and bar/beverage service		X				
Provide and encourage in-room dining service		X				
Implement strict cleaning and disinfection protocols (SOPs)	X	X		X	X	
Clean/disinfect frequently touched surfaces regularly		X	X	X	X	
Clean/disinfect using separate cloths and buckets					X	
Use single-use, disposable cleaning equipment					X	
Dispose wastewater from cleaning as sewage					X	
Disinfect exercise equipment in gyms					X	
Disinfect food preparation areas / trolleys			X		X	
Wear masks and use disinfectants in hair salons					X	
Maintain SOPs for laundry of linen and clothing					X	
Wash all textiles at a hot-water cycle (90°C) and add laundry detergent			X		X	
Do not shake dirty laundry			X			
Use touchless payment options		X			X	

Specifically for crew						
Refrain from using common areas on board (crew)	X		X			
Cancel all face-to-face employee meetings			X			
Instruct crew members to wear mask when outside of cabins			X			
Close all crew bars			X			
Implement social distancing of crew members when working			X			
Disinfect own work areas (crew)	X					
Return to cabin immediately after work hours (crew)	X					
Remain in cabin during rest hours (crew)	X					
Receive and eat all meals in cabin (crew)	X		X			
Prioritize advanced respiratory protection by crew belonging to high-risk groups					X	
Prior to/ Upon disembarkation						
Monitor health prior to disembarkation	X					
Ensure all shore excursion tour companies facilitate physical distancing		X				

Complete PLF pre disembarkation						X
Clean and disinfect after disembarkation						X
Screening and Diagnosis						
Before/Upon embarkation						
Perform day of embarkation screening for signs & symptoms		X	X			
Test newly embarking crew on day of embarkation and 3-5 days thereafter		X	X			
Screen embarking and disembarking crew and non-crew				X		
Require al contractors and visitors expected to remain on board ≥7 nights to quarantine			X			
Test all specimens for a ship’s crew at same laboratory			X			
On board the ship						
Maintain screening and surveillance protocols to detect covid-like illness		X	X			X
Align testing protocols with CDC guidance		X				
Maintain on board capacity to conduct viral tests for SARS-COV-2		X	X	X		

Compensate any limitations in capacity with agreements with testing facilities on shore				X		
Perform routine-COVID-19 screening testing and monitoring of crew		X	X	X		
Prior to/ Upon disembarkation						
Test symptomatic passengers by PCR upon arrival in port	X					
Risk containment / mitigation						
Before/Upon embarkation						
Quarantine all embarking land-based crew for 14 days			X			
On board the ship						
Designate isolation/ quarantine cabins in areas separate from other cabins		X	X	X		X
Isolate patients in sick bay or single cabins with private bathroom	X	X	X			
Minimize contact between travelers in quarantine and support staff		X				
Deliver meals to individual cabins with no face-to-face interaction		X	X	X		
Package meals in disposable dining ware with single use cutlery			X			
Wear PPE when in contact with sick patients / entering their room	X	X				

Identify and test all close contacts, as soon as possible	X	X				X
Quarantine all contacts for 14 days						X
If difficult to identify, all passengers are considered contacts						X
Define high risk and low risk exposure contacts				X		
Maintain strict cleaning and disinfection during case management	X			X		
Disinfect medical facilities daily					X	
Avoid splashes when cleaning toilets, sinks and sanitary facilities					X	
Steam clean or discard soiled mattresses					X	
Ensure cabins housing isolated passengers are not cleaned by crew members		X	X			
Manage contaminated waste			X	X		
Treat food waste from cabins of suspected cases or contacts as infectious					X	
Manage soiled linens and towels			X			
Place temporary HEPA filters over the vents					X	

Use surveillance cameras to ensure compliance with quarantine protocols		X	X			
Consider putting ship on quarantine (worst case measure)				X		
Prior to/ Upon disembarkation						
Ensure no contact of case with other passengers during disembarkation	X	X		X		X
Ensure separate pathway to disembark with personal belongings (luggage)		X				
Thoroughly clean and disinfect isolation cabin	X					
Quarantine unvaccinated seafarers away from ship	X					
Arrange for repatriation of passengers and crew				X		
Complete Attestation for Commercial Transportation of Disembarking Crew			X			

Table 22: Consolidation of recommendations for influenza outbreak – by public health pillar

	SHIPSAN (2016, 2011)	CDC (2016)	CDC (2019)
Prevention			
Before / Upon Embarkation			
Get vaccinated annually for influenza		X	
Vaccinate crew and passengers at least 2 weeks before voyage	X	X	X
Disseminate health questionnaire upon embarkation	X		
Deny boarding if signs & symptoms	X	X	X
Postpone travel when sick		X	X
Discuss antiviral treatment and chemoprophylaxis before travel			X
In case of pandemic, deny boarding	X		
In case of pandemic, request vaccination	X		
In case of pandemic, request and record epidemiological information	X		
On board the ship			
Implement hand washing / hand hygiene	X	X	X
Implement cough and sneezing etiquette	X	X	X

Implement disposal of dirty tissues protocol	X		
Implement social distancing	X		X
Eliminate handshaking events	X		
Focus on regular cleaning and disinfection of ship accommodation spaces	X	X	
Prior to/ Upon disembarkation			
Follow safe food and water precautions when eating off the ship			X
Screening and Diagnosis			
Before / Upon Embarkation			
Educate crew to recognize signs and symptoms	X		
Perform medical screening during embarkation to identify ill passengers			X
On board the ship			
Initiate case finding, upon identifying influenza outbreak	X		
Have rapid diagnostic influenza tests available onboard the ship	X		
Consider clinical diagnosis of influenza		X	
Risk containment / mitigation			
On board the ship			

Isolate patients presenting symptoms for at least 24 HRS after free of fever	X	X	X
Isolate passengers who embark with symptoms of ILI		X	X
Isolate passengers who become sick with ILI en route		X	
Implement respiratory hygiene and cough etiquette		X	
If in common areas, affected passengers should practice social distancing/wear masks		X	
Keep interaction with sick people as limited as possible		X	
Avoid touching eyes, mouth, and nose		X	
Monitor health of close contacts for 4-5 days post exposure		X	
Follow protocols for disinfecting /cleaning materials contaminated by body fluids	X		
Use PPE (masks and disposable gloves) appropriately	X		
Manage waste properly (infectious waste managed separately)	X		
Avoid cross-contamination	X		
Consider early anti-retroviral treatment to control an outbreak		X	
Prior to/ Upon disembarkation			
Disembark ill persons together with luggage from separate area of ship	X		

In case of pandemic, isolate cases for at least 24 HRS after free of fever	X		
Consider quarantine of crew/passengers without symptoms but suspected to be infected	X		
Stay inside home or hotel in the city of disembarkation and refrain from further travel until at least 24 HRS after free of fever		X	

Table 23: Consolidation of recommendations for gastrointestinal infections outbreak – by public health pillar

	SHIPSAN (2016, 2011)	CDC (2016, 2018, 2019)	HPA / MCA (2007)
Prevention			
Before / Upon Embarkation			
Request pre-embarkation health questionnaire	X		X
Screen symptomatic individuals and prevent from coming aboard		X	X
Prevent ill patients from boarding		X	
On board the ship			
Promote effective hand hygiene – thorough hand washing	X	X	
Provide instructions on hand washing and health advice	X		
Apply standard cleaning and disinfection procedures	X		
Have disinfectants against norovirus always available	X	X	
Perform environmental cleaning	X		
Use PPE (disposable gloves) when cleaning	X		
Provide information on reporting of symptoms	X		
Provide instructions on hand washing and health advice	X		

Emphasize on need to shower before using recreational water amenities	X		
Avoid contact with ill people		X	
Prior to/ Upon disembarkation			
Follow safe food and water precautions when eating off the ship		X	
Screening and Diagnosis			
On board the ship			
Diagnose as early as possible	X		
Ensure clinical support to diagnose cases	X	X	
Use pre-agreed questionnaire maintained in ship's medical center	X	X	X
Collect fecal specimens for analysis during every outbreak	X	X	X
Collect and analyze epidemiological data to identify cause of outbreak	X		
Investigate galleys, potable water supplies or recreational water areas	X	X	X
Risk containment / mitigation			
On board the ship			
Isolate patients presenting with GI symptoms- minimum 24 – 48 HRS	X	X	X
Provide hygiene and medical support in individual cabins	X	X	

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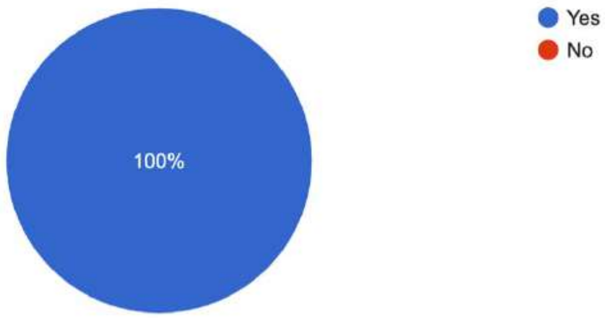
Isolate individuals who are at high risk		X	X
Isolate and manage confirmed cases according to enteric assessment			X
Keep passengers in own cabin until 24HRS after resolution of symptoms	X		X
Provide health advice to close contacts	X		
Encourage use of cabin ensuite facilities for a further 24 HRS			X
Relocate unaffected cabin companions in alternate accommodation			X
Do not use communal facilities during isolation			X
Offer and advise to get room service	X		X
Stop self-service of food and beverages	X		
Consider need for time limited control measures			X
Institute recommended environmental cleaning regime / disinfection	X		X
Apply standard protocol of body fluid spillage in public area	X		
Establish dedicated cleaning team for environmental cleaning of cabins of affected passengers	X		X
Implement enhanced cleaning to mitigate risk of continuation in next voyage	X		

Use dispensable aprons and gloves when examining passengers with GI symptoms			X
Prior to/ Upon disembarkation			
Disembark ill persons together with luggage from separate area of ship			X
Accommodate sick patients in specified hotels until recovery			X

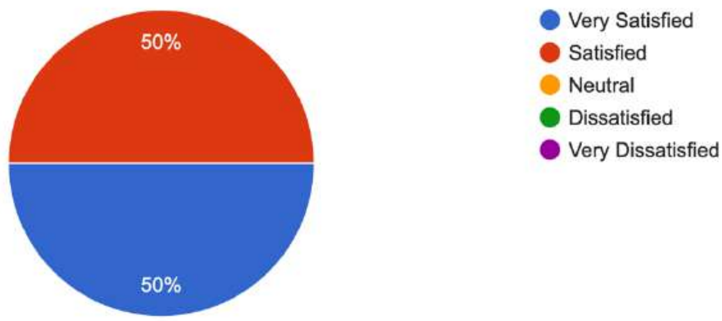
APPENDIX 2: CDF Platform questionnaires from Pilot's participants

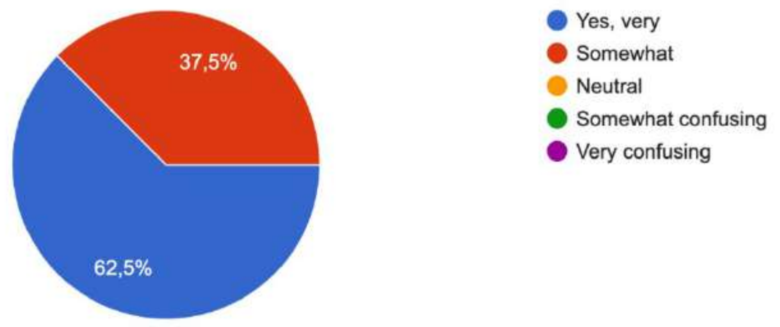
Consent: Having read and understood the above, I declare that I am over 18 years old and I provide my informed consent for the use of the anonymized data I shall be providing for the purposes of the preparation of a scientific publication.

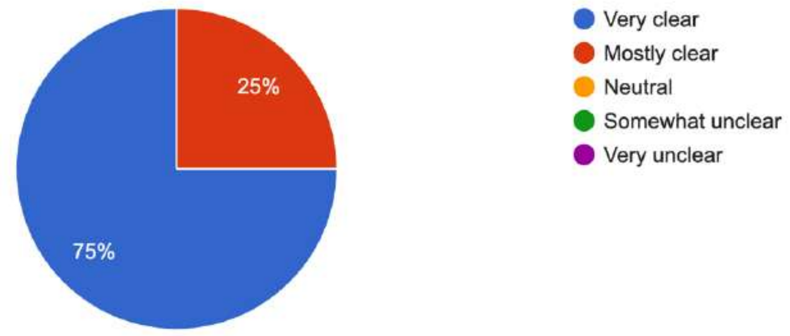


Question 1: How frequently do you think you could use the CDF Solution software onboard ship?

Question 2: How satisfied are you with the design of the graphical user interface, overall?

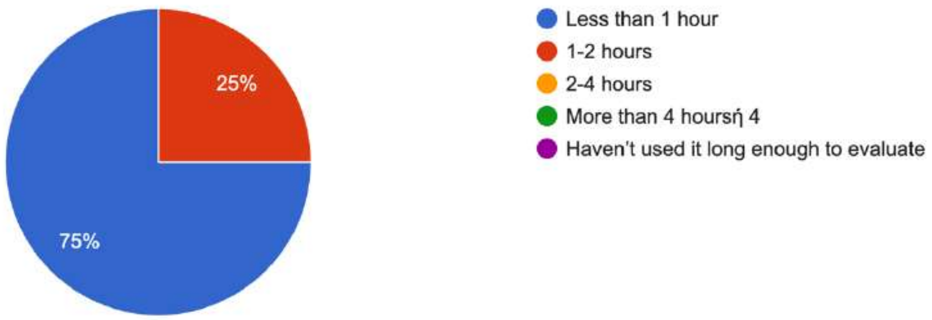


Question 3: Is the layout of the interface easy to use in an intuitive manner?

Question 4: Are the main features of the software accessible easily from the dashboard?

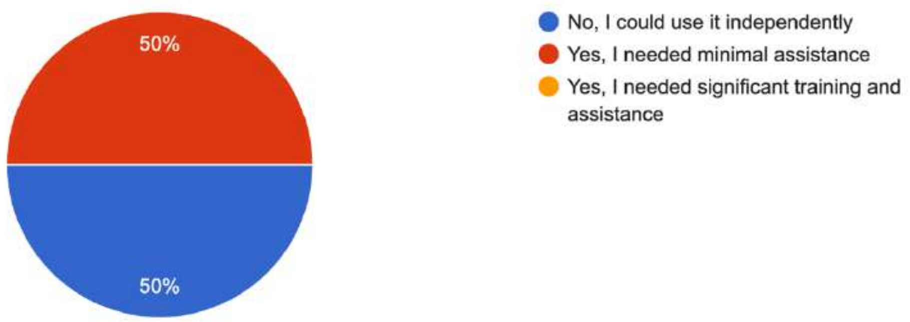
Question 5: Are the icons and buttons used in the interface clear?


Question 6: Do you think it is easy to learn how to use the CDF software (as a first-time users)?

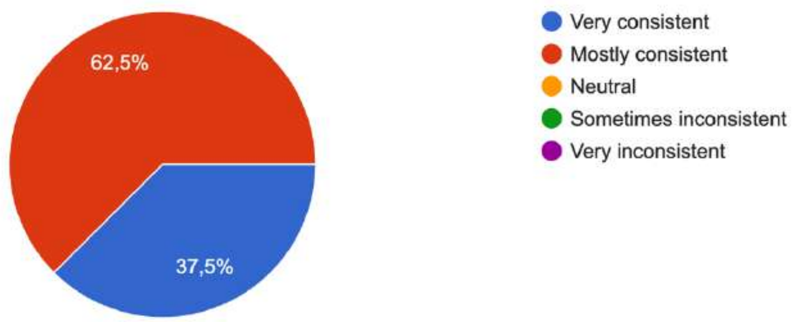
Question 7: How long did it take for you to feel that you can comfortably use the CDF software?



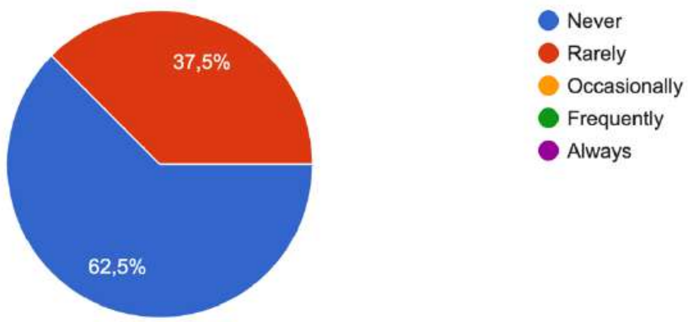
Question 8: Did you need any training or assistance to use the CDF software?



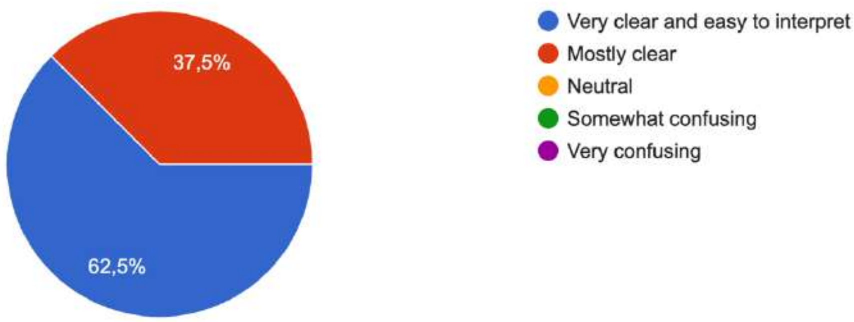
Question 9: Do you find that the CDF software's performance during the time you use it is consistent to its results?



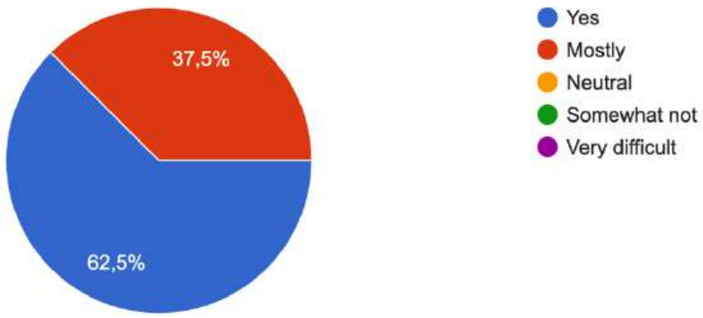
Question 10: Have you experienced any software crashes or errors during the time you used it?



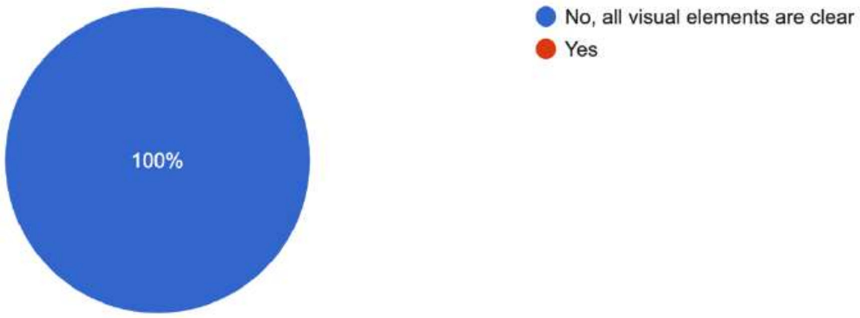
Question 11: Are the colour codes used in the CDF software clear, for disease risk levels identification and provision of alerts?



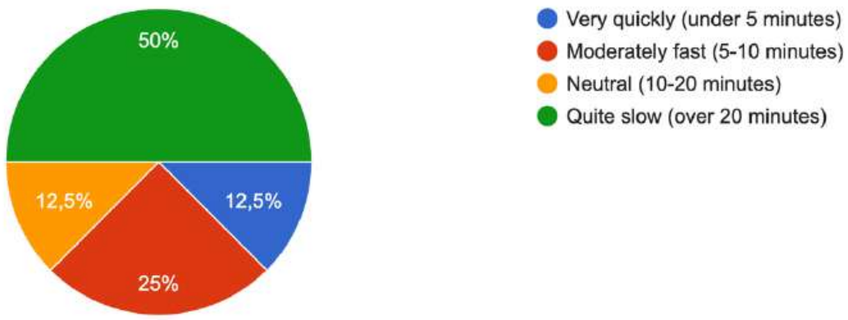
Question 12: Do you think that the colors and their contrast are design to make it easy to distinguish different information?



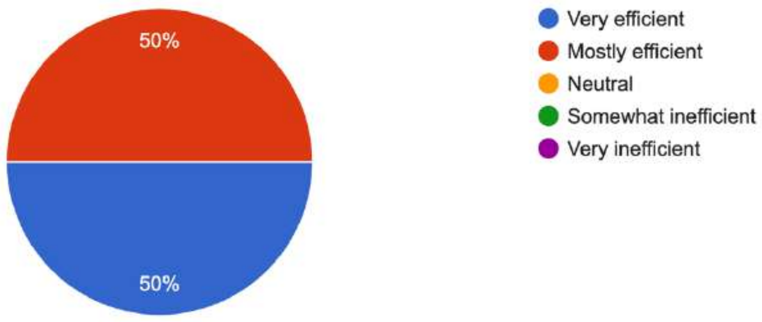
Question 13: Are there and visual elements or colors that you seem to find hard to read or unclear?



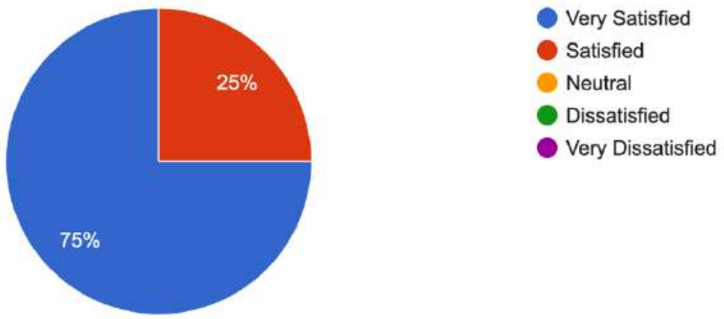
Question 14: How long does it typically take you to report a communicable disease and update patient status without the CDF software?



Question 15: How efficient do you feel the CDF software is in supporting you in disease detection and reporting onboard ship?



Question 16: Are you satisfied with the CDF Solution software overall?



Question 17: Would you recommend the CDF software to others for use?