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# Scenarios for sensors and actuators deployment to prevent and mitigate epidemics on cruise ships.

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## Abstract

Following the COVID-19 outbreaks on board cruise ships in 2019, the naval community is considering how the rapid development of the Internet of Things could contribute to better preventing and mitigating outbreaks on cruise ships. A consortium of experts through the European Union-funded project Healthy Ship for You (HS4U) analyzed the high-level requirements and the state of the art of sensors and actuators solutions that could be used. Technologies for symptom detection, disease recognition, and passenger localization were identified, and approaches for surface, air and duct purification, and for communication between the crew, the public, and authorities were considered. Coupling the requirements with the state of the art allowed the consortium to propose several feasible scenarios for the deployment of sensors and actuators aboard a cruise ship. The architecture of a

digital platform utilizing the sensors and actuators to assist the crew in preventing and mitigating an outbreak is also described. The information gathered here is expected to have a broad impact outside the HS4U consortium: (1) on the one hand, it aims to familiarize the cruise ship stakeholders with the technologies offered by the Internet of Things for health-related matters and to consider their adoption in the near future; and (2) on the other hand, it may contribute to the development of regulations regarding outbreak management by competent authorities.

## Introduction

Since 2020, the heavy toll of the global COVID-19 pandemic on the cruise industry has been well-documented. Highly publicized outbreaks on cruise ships in the early days of the pandemic were followed by reported cases of the virus being widely spread in passengers' home countries by those returning from cruise ships. By the end of March 2020, cruises were halted worldwide, and travel restrictions increased. This ultimately reduced the number of cruise passengers from 30 million in 2019 to 6 million in 2020. It is estimated that cruise lines lost \$77 billion between March and September 2020 alone (Muritala et al., 2022; Syriopoulos et al., 2022).

Meanwhile, the fight against COVID-19 on land has been bolstered by the use of the Internet of Things (IoT), and its myriad of sensors and actuators (Citrawati et al., 2023). But within the cruise ship industry the use of these solutions has been and remains minimal. Accordingly, recommendations for managing COVID-19 on board cruise ships have been published and revised by various international agencies (such as European Medicines Agency) in recent years, but they do not include any IoT solutions (European Medicines Agency, 2022), whereas such solutions have been widely heavily used by land-based agencies.

One of the goals of the Horizon Europe project Healthy Ship for You (HS4U<sup>1</sup>) is to evaluate how the current advances in the field of IoT, especially in the area of healthcare sensors and actuators (S&A), could be applied to the prevention and mitigation of outbreaks on board large passenger vessels, particularly cruise ships and ROPAX (roll-on/roll-off passenger) vessels.

To evaluate the feasibility of achieving this high-level objective, the consortium formulated a series of high-level technical, operational, and business requirements. It then analyzed the state of the art to identify a number of promising S&A-based technology solutions that meet these high-level requirements. It resulted in scenarios for S&A deployment aboard cruise ships. The present paper reports on the highlights of this process.

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<sup>1</sup> <https://hs4u.eu/>, last accessed May 24<sup>th</sup>, 2023

## **High level S&A requirements**

### **Outbreak-related requirements**

Relevant outbreaks on cruise ships have been identified by industry stakeholders in documents such as SHIPSAN (EU SHIPSAN Joint Act, 2016) and the US Vessel Sanitation Program (U.S. Department of Health and Human Services et al., 2018). These diseases include gastroenteritis, influenza-like illness, legionella and vaccine-preventable diseases (e.g. measles, rubella and varicella).

To address such diseases on cruise ships, the HS4U project listed two main objectives for S&A:

1. The first objective aims to detect an outbreak, i.e. to detect as early as possible any person on board with an infectious disease. This breaks down into two steps: detection of a sick person and identification of the actual disease. The latter (i.e. not just the detection of symptoms) is particularly critical for initiating the appropriate outbreak mitigation measures, as these are disease-specific. To detect patient zero, exhaustive monitoring of passengers and crew members is required. To minimize the number of contact cases after initial contamination, detection as close as possible to the onset of symptoms, or even before, is needed. Considering that health-related data is to be collected, extreme care should be taken with regard to data protection. Non-anonymized health-related data should remain confidential throughout its life cycle. People who may have access to such data, beyond the ship's medical personnel, should be carefully defined based on the regulatory framework.
2. The second objective aimed at outbreak prevention and mitigation. One aspect directly targets pathogens: prevention of pathogen colonization (on surfaces and/or in piping systems) and transmission (through air, water or surfaces, including piping systems). This requires solutions for permanent and/or continuous and/or automatic disinfection of surface, air and piping. The second aspect aimed to minimize exposure of people on board: detecting exposure by direct contact or by staying in a contaminated area; enabling confinement procedures; enabling smooth information transfer (between crew, passengers, and authorities).

### **Business requirements**

The business requirements of the cruise ship stakeholders (ship operators, ship owners, ship hotel managers) were captured through interviews and workshops.

The companies *Celestyal Cruises* and *COLUMBIA blue* are members of the HS4U consortium and contributed to the following high-level requirements.

1. The cruise ship industry is a luxury business. Priority must be given to passenger acceptability of the proposed solutions. This includes respecting and anticipating ethical and privacy concerns. To ensure acceptability, dual use of the solutions must be considered. For example, a smart wearable device used for outbreak monitoring can be positively marketed as a self-health tool provided by the cruise line; or it can be used to replace the key cards for room and restaurant access.
2. The cruise industry is also a mid-volume market: passengers number in the thousands, so the cost per passengers must be highly controlled and the solutions selected must be commercially viable in the thousands.
3. To limit costs, the solutions should require minimal additional crew effort to operate and maintain the systems.
4. As far as possible, the solutions should be transferable from ship to ship (i.e. when a ship changes ownership or is retrofitted, most technologies should be deployable to another ship). This implies the interoperability of the solutions, i.e. the ability to adapt them smoothly to different ship IT infrastructures.

Quantifying the affordability of the costs remains an open discussion. As seen in the case of COVID-19, in the event of a large outbreak on board, all passengers may have to be sent home and the ship's operations may have to be halted for several days or weeks. This can cost the ship's owners millions of dollars, not to mention the damage to their reputation. But, with the exception of the COVID-19 crisis (an extreme event), this is a rare scenario.

On the other hand, from a legal perspective, ship stakeholders are only required to implement on board the health-related measures defined in the applicable regulatory documents. Determining the affordability of implementing additional outbreak prevention and mitigation measures beyond those required by regulations is a risk and liability management issue. It seems reasonable to assert that the cost per passenger should not exceed a small percentage of the revenue per passenger. To put concrete numbers on this, the website [cruisemarketwatch.com](https://cruisemarketwatch.com)<sup>2</sup> reports that, in average, in 2021, passengers spent \$214 per day on cruises with an average length of 7 days. The same source also reports the breakdown of this spending into operator expenses, from 14.5% of various operating costs down to 3% interest expense, including 11% of ship fuel costs or payroll, resulting in 12.7% profit before tax. Setting aside 0.5 to 1% of the profits – \$1 to 2 per day per passenger – to insure against onboard outbreaks (which can cause millions of dollars in losses) can be argued as a reasonable amount compared to other expenses. Projected over a year, this amounts to an annual budget of approximately \$500,000 per year for every 1,000 passengers.

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<sup>2</sup> <https://cruisemarketwatch.com/financial-breakdown-of-typical-cruiser/>, last accessed on June 1<sup>st</sup>, 2023

## Ship integration constraints

### Overview

Any S&A solution proposed for deployment on board must comply with existing rules and practices for ship design. All vessels must be constructed in accordance with prevailing rules and regulations to ensure their safe and secure operation throughout their lifetime. Drivers of legislation, both national and international, include statutory requirements (i.e. legal requirements), classification societies, flag states, international standards, and port authorities.

Cruise ships are specialized passenger vessels, with no cargo deck, designed for the commercial transportation of passengers in overnight accommodations. They can carry a large number of passengers and crew members, both for ship operations and hospitality, making safety on board of paramount importance.

A ship is made up of multiple systems into which each S&A solution must seamlessly integrate. A ship is a *system of systems*, consisting of various smaller systems that work together to achieve the ship's function. They are generally categorized as hull and machinery; deck, engine, and hotel machinery and equipment; in engine propulsion and power generation systems; auxiliary systems for cooling, fuel, and lubrication; systems for handling waste and sewage; systems for providing hot and cold potable and recreational water; firefighting and life-saving equipment; and automation and communication systems.

All the subsystems are integrated within the spatial arrangement of the vessel. Successful system integration requires a holistic understanding of the ship as a system so that no subsystem negatively interferes with another. Each system may consist of piping components and valves, tanks, electrical and mechanical equipment etc. that must be coordinated. The engineering design is guided by the relevant regulations, the functional requirements of the system and the needs of the customer. Based on the specific functionality that the system has to perform, the marine engineer plans for its interconnections and arrangements. All of the necessary information is included in the ship's drawings. Some of the most basic drawings are the general arrangement plan (i.e. GA plan), the capacity plan, the deck arrangement plans, the engine room machinery and electrical arrangement plans, the electric load analysis, the wiring diagram of power, the wiring diagram of communications, the wiring diagram of alarm and monitoring, the wiring diagram of lighting, the fire control plan, the piping diagrams.

With regard to epidemic management on board with S&A, the following systems are relevant for further discussion: piping and HVAC systems, as they are avenues of disease transmission, can contain and grow pathogens, and can be included in outbreak mitigation protocols; power generation systems, since the S&A must be powered; alarm and monitoring systems, to control and monitor the S&A; communication systems, to ensure that the S&A do not interfere with critical communications, and for use by the S&A for communication.

## Piping systems

Focusing on the piping systems on board, the systems of most interest to epidemic management are: fresh and potable water systems (including desalination plant, if applicable); ventilation systems; sanitary system. Note that the fire and safety system is not directly relevant to epidemic management, so is not listed here, but a similar approach to fire zones could be used for virus containment.

A piping and instrumentation diagram, or P&ID, shows the piping and related components of a physical process flow. Various operational scenarios are integrated into the piping system. For each, the appropriate valve arrangements, types and instruments are selected. Valves are used in a piping system to regulate or stop the liquid flow. Various types exist onboard a vessel, like butterfly valves, globe valves, ball valves, gate valves, non-return valves etc. The valves may be operated either manually by the crew or remotely through a control station. The open/close status of some manually operated valves can be displayed at a control station. The main control stations are located in the Engine Control Room (ECR), the Engine Control Console (ECC), and in the Wheelhouse, the Bridge Control Console (BCC). Remote control is generally enabled by electrical, pneumatic or hydraulic means. The various on-board sensors and all actuation means are shown in the P&IDs.

The piping system is usually monitored for pressure, temperature, and flow. The type, number and localization of monitoring instruments are defined based on the ship's structural design and on the functionality of the specific system. The signals from the instruments, valves and equipment are usually gathered at electrical panels that are connected with the Alarm and Monitoring system of the ship.

In this context, S&As for outbreak management are a new functionality that needs to be integrated into the ship's design. Any piping system can either be retrofitted with S&A or retrofitted by changing part of its design, including new valves or restricted connections between piping systems for existing vessels. On new vessels, a piping system can be redesigned using the best practices identified from experience or the requirements of codes and regulations.

## Grey and black water piping system

There are two types of wastewater piping systems on board. The first is the *black water system*, which handles all of the sewage. As defined in MARPOL Annex IV<sup>3</sup>, "sewage" refers to water and other wastes from toilets and urinals; drain-

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<sup>3</sup> International Convention for the Prevention of Pollution from Ships - Annex IV Prevention of Pollution by Sewage from Ships entered into force 27 September 2003. <https://www.imo.org/en/about/Conventions/Pages/International->

age from medical premises (dispensary, sick bay, etc.) through wash basins and scuppers located in such premises; drainage from spaces containing living animals; or other wastewater when mixed with the drains defined above. The second is the *grey water system*, which manages drainage from dishwashers, galley sinks, showers, laundry, baths, and washbasins, and does not include drainage from toilets, urinals, hospitals. With regard to early disease detection, the black water system is the most critical: high virus loads can be detected there in the early stages of an outbreak.

Ships use a variety of sewage disposal systems depending on their size and technology. Either gravity or vacuum toilets can be found. Sewage is discharged either into common sewer lines leading to the ship's side and overboard through storm valves, or into collection and storage tanks, with or without aeration facilities, in which the sewage is retained for disposal on land or at sea, or into sewage treatment systems incorporating a combination of collection and treatment tanks, with processes designed to eliminate organic and sanitary pollutants in the sewage into effluent suitable for discharge into the sea without harmful effects. Ship requirements for sewage handling are detailed in MARPOL Annex IV.

On large passenger ships, blackwater is typically collected in the holding or treatment tanks using vacuum collecting systems. Depending on the size and number of passengers, 4 to 10 vacuum collecting units are installed per ship. Due to increasing environmental awareness, large passenger ships are being equipped with Advanced Wastewater Treatment (AWT) Systems using biological sewage treatment and membrane or flotation technology. Even though MARPOL Annex IV does not regulate greywater, AWTs are often designed for the vessel's entire wastewater system, which consists of both black and greywater discharges. The high specific wastewater volumes, up to 350 liters per person and per day, makes the installation of sewage treatment plants a preferred option on board large passenger ships: as the operators are allowed to discharge the treated effluent directly to the sea, the construction of large-capacity sewage holding tanks is avoided which is valuable as space is a limited resource on board ships.

## **HVAC system**

HVAC refers to the heating, ventilation, air conditioning and cooling systems onboard a vessel. The ventilation system is a complex system with high power consumption. Temperature, pressure and humidity must be monitored to ensure proper operation. Ship ventilation systems have different requirements depending on the destination of the compartments and the type of ship. For example, there are compartments where natural ventilation is sufficient. Other compartments re-



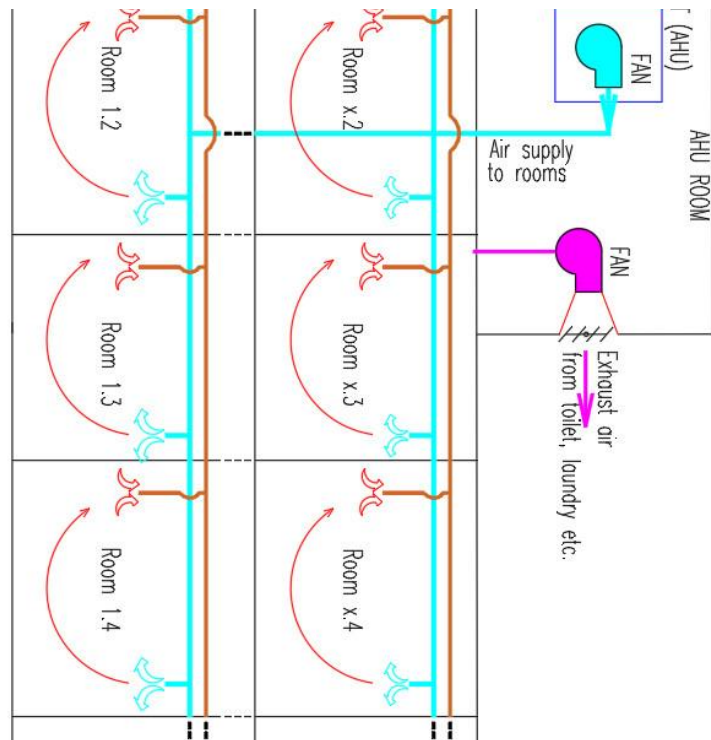
quire forced ventilation by means of exhaust and/or intake fans, while still other compartments require ventilation by means of an air handling unit. In the case of living quarters, standard ventilation and air conditioning systems are used to provide cooling or heating of the compartments and the required supply of fresh air. Air purifiers may also be used (Dbouk et al., 2021).

In a standard ventilation and air conditioning system (Figure 1), fresh air supplied through openings in the vessel structure is mixed inside the Air Handling Unit (AHU) with air recirculated from the rooms it serves. At the inlet to the AHU the recirculated air can be mixed with the fresh air from outside to equalize the temperature difference between the hot and cold air. Based on the volume of the space and the mixing ratio at the AHU, the air is forced into the distribution piping that served the area. An AHU generally consists of a fan that draws air through a mixing chamber for fresh and re-circulated air, filters, heating coil (steam), cooling coil for evaporative refrigerant, and steam humidifier nozzles.

The air handling unit can supply air that has been heated or cooled. Only one function can be active at a time. When the outdoor temperature exceeds the required set point, the control valve to the heaters is closed and the cooling control system operates. When the outdoor temperature is below the set point, steam regulation is initiated by opening the control valve to the heaters and closing the valves in the refrigerant lines. A temperature sensor in the supply line controls the cooling and heating. Should the AHU fan stop or trip, the cooling and heating valves will automatically close.

In large ships, there are multiple AHUs on different decks to serve different areas, defining HVAC zones. An HVAC zone is a space or group of spaces that are independently controlled for temperature, humidity and air distribution. Zones are directly related to fire zones and are grouped by cabin and public areas. A zone usually consists of common ductwork served by an air handler.

Compared to the generic configuration described above, cruise ships have specifics: there are always supply and return ducts with two fans in passenger areas, plus an extraction fan from toilets. Cruise ships use chilled water systems in the state of direct refrigerants to AHU. The chilled water is produced centrally in the engine room and can thus provide cooling in other areas too (e.g. galley equipment).



**Fig 1.** Common ventilation and air conditioning system. Reproduced from (Mihai and Rusu, 2021)

## State of the art for S&A for epidemic management on cruise ships

### The Internet of Ships

Based on the requirements listed in the previous section, the state of the art in S&A was investigated to identify suitable solutions. Overall, it appears that the field of Internet of Things (IoT) on ships is gaining traction. Initial research in this area was conducted by Paik et al. who detailed the use of wireless sensor networks as decision support tools on ships (Paik et al., 2010, 2009). Later, Aslam et al. proposed the “Internet-of-ships” paradigm, which includes ship applications of S&A such as safety enhancements, route planning and optimization, collaborative decision-making, automatic fault detection and preventive maintenance, cargo

tracking, environmental monitoring, energy-efficient operations, and automatic berthing (Aslam et al., 2020). However, as of May 2023, the concept of the “Internet-of-ships” does not include healthcare applications: bibliographic searches combining “ship”, “healthcare”, and “sensor” (and their synonyms) remain entirely fruitless.

Still, more specific keywords yield interesting references. In particular, the COVID-19 pandemic inspired several studies: Mihai and Rusu reviewed in 2021 how optimizing the operation of the ship ventilation systems could prevent the spread of diseases (Mihai and Rusu, 2021). In addition, Liu et al. (Liu et al., 2022) discussed people tracking for the mobile ship environment (to subsequently allow contact tracking) (Liu et al., 2022). Furthermore, on a directly related topic, Liston et al. (Liston et al., 2022) addressed the acceptability and usability of location-support technologies for cruise ships, but applied this to the issue of ship evacuation (Liston et al., 2022).

Another driver for the use of IoT on ships is the “silver economy”, i.e., the idea of using IoT to make cabins more suitable and accessible for elderly passengers using the IoT. This has been elucidated, for example, as a *smart cabin* outfitted to detect fall events (Vujovic et al., 2017). Several alternative approaches have also been proposed, whereby the e-cabin provides insights into smart maintenance scheduling, energy usage optimization and detection of security issue (Barsocchi et al., 2019; Nolich et al., 2019; Plaza-Hernandez et al., 2021). In these projects, the focus was primarily placed on comfort as opposed to healthcare.

## **Health-care S&A: applicability to ships?**

Considering the scarcity of the literature, HS4U endeavored to create an inventory of S&A technologies for outbreak prevention and management that could be adapted to the cruise ship context. With respect to sensor solutions for outbreak detection, the results of this inventory are reported in several chapters of this book: Almeida et al. discuss existing solutions for detecting symptomatic passengers (Almeida et al., n.d.) while Lebental describes solutions for identifying infectious diseases (Lebental, n.d.). In terms of actuators to prevent and mitigate outbreaks, Almeida et al. also discuss the human-related tools: how to track contact cases and passenger localization on the ship, and how to share information between the crew and the public.

As for solutions to combat pathogens, transmission of pathogens in closed indoor spaces occurs by direct or indirect contact such as physical contact (e.g., handshake), fomite (e.g., clothing and furniture), droplets (5–10 $\mu$ ), and aerosols (less than 5 $\mu$ ) (Dbouk and Drikakis, 2021, 2020; World Health Organization, 2014). Many disease outbreaks can also be attributed to the presence of microbially contaminated surfaces. Microbes, for example, can thrive and multiply in a moist environment when attached to any artificial surface, often forming a biofilm that provides a protective environment for microbial survival under chal-

lenging conditions (Mah et al., 2003). Viruses, on the other hand, do not replicate outside a living microorganism but can be easily transmitted via inanimate surfaces simply by settling on a surface. Thus, contaminated surfaces in close proximity to infected individuals can serve as a medium for the spread of infections from animate sources to others via contaminated inanimate surfaces (Kramer and Assadian, 2014). An important example is *norovirus*, which is responsible for more than 90% of nonbacterial and about 50% of all epidemic gastroenteritis cases, causing an estimated 267 million infections worldwide each year. One of the main routes of transmission of norovirus is through contaminated surfaces, either by touching an infected person or by droplets of aerosolized vomit from an infected person.

Existing disinfection or contamination removal techniques typically rely on UV light and filters to control airborne pathogens or chemical disinfection to eliminate surface pathogens. In fact, surface treatment has shown to reduce the microbial and viral burden on surfaces, thereby reducing disease transmission and development (Weber et al., 2010). However, conventional sanitization methods that rely on chemical agents have been shown to be inadequate in preventing recontamination of surfaces and can actually promote the selection of drug-resistant strains. As a result, more than 50% of surfaces remain persistently contaminated (Caselli, 2017; Romão et al., 2011).

With regard to air purification, Dbouk et al. discuss the role of air purifiers in reducing indoor virus transmission (Dbouk et al., 2021). Filtration is a widely accepted method of removing airborne pathogens and is particularly effective when used in conjunction with UV light. The addition of filters to central ventilation systems is likely to reduce the airborne load of infectious particles. However, the costs associated with energy consumption and the need to periodically replace filter media and UV lamps make cost-effectiveness a critical factor to consider (Kabrein et al., 2016). Furthermore, if not properly designed or operated, the HVAC system can actually accelerate the transmission of the airborne disease throughout whole buildings (Feng et al., 2021). In addition, HVAC systems themselves can be a significant contributor to indoor biological pollution and cause disease outbreaks, as certain microorganisms thrive in the dust of air conditioning units that provide the ideal temperature and humidity conditions (Lv et al., 2017). Overall, poor installation and low maintenance of HVAC systems is a significant factor in disease propagation and transmission due to high risk of infestation with dangerous pathogens such as *Aspergillus spp.*, which can cause lung disease and allergic asthma, or *Legionella spp.*, which can cause a severe pneumonia called Legionnaires' disease (Azara et al., 2006; Schulster and Chinn, 2003).

On the whole, it seems that extensive sanitation has become the primary approach in the prevention and disruption of disease outbreaks, despite the risk of accelerating the development of multidrug resistant (MDR) microorganisms. In the search of new effective and sustainable approaches to infection control, HS4U brings to light two approaches: colloidal silver coatings and probiotics. The state of the art, potential and challenges of applying colloidal silver as an anti-pathogen material in the naval sector are discussed in the chapter by Somarriva et al. of the present book (A. Sommariva et al., n.d.).

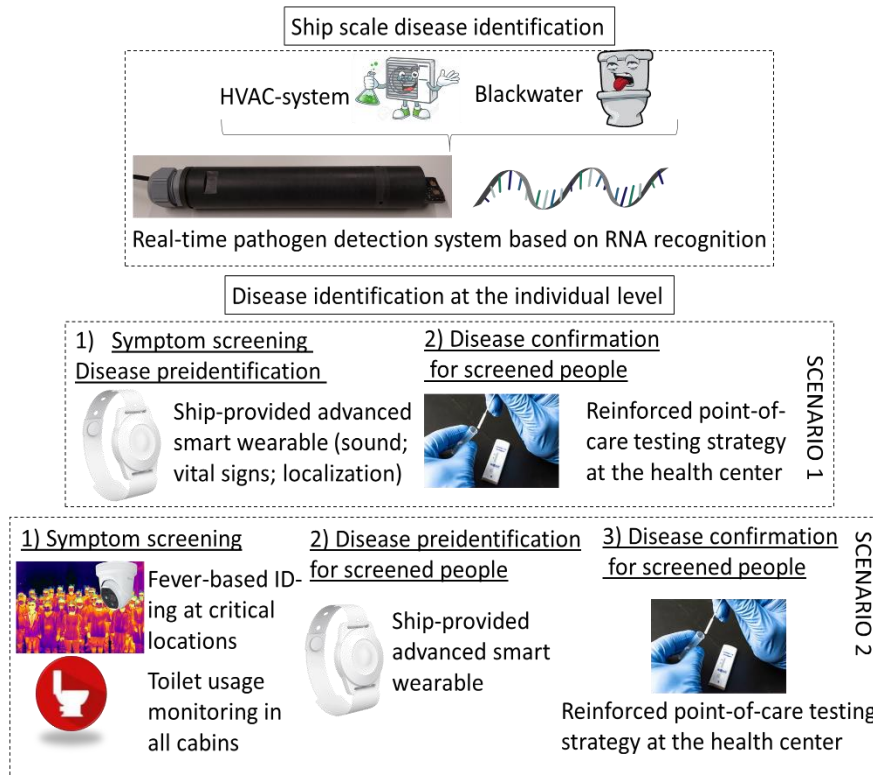
With regards to probiotics, their value in “attacking” surface pathogens is being actively explored (Al-Ghalith and Knights, 2015). The accumulation of studies on the effect of probiotics on pathogens on inanimate surfaces has shown that the introduction of certain probiotic strains can antagonize pathogen growth and reduce pathogen biofilm formation through mechanisms of competitive exclusion (competition for resources) (Falagas and Makris, 2009). Bacterial strains belonging to *Bacillus* genera are among the most commonly used probiotics, probably due to their ability to form spores, propagate in various environments, and are considered GRAS safe. Other factors contributing to the high potency of *Bacillus* spp. are the production and secretion of various antibiotic compounds and significant amounts of proteolytic enzymes with outstanding stability (Contesini et al., 2018; Mannanov and Sattarova, 2001; Pinchuk et al., 2001). It has been shown that *Bacillus subtilis* strains expressing extracellular enzymes can effectively inhibit SARS-CoV-2 virus infection by degrading spike proteins (Tanikawa et al., 2022).

Different formulations of surface cleaners based on probiotics containing *Bacillus* spp. have shown remarkable results when applied topically on surfaces compared to the common cleaners such as soap or 70% ethanol solution (D’Accolti et al., 2023, 2018; Stone et al., 2020), in some cases showing a stable reduction of surface pathogens up to 90% more than conventional disinfectants, without selecting resistant species (Caselli, 2017). Despite its potential benefits, the use of probiotics for topical application also has some drawbacks similar to those of conventional disinfectants. These include being a time-consuming process, requiring frequent reapplication, and not being able to effectively reach all the small areas where microorganisms may hide and continue to proliferate. *Ecosense LTD.*, a member of HS4U consortium, is addressing these issues as described in a later section.

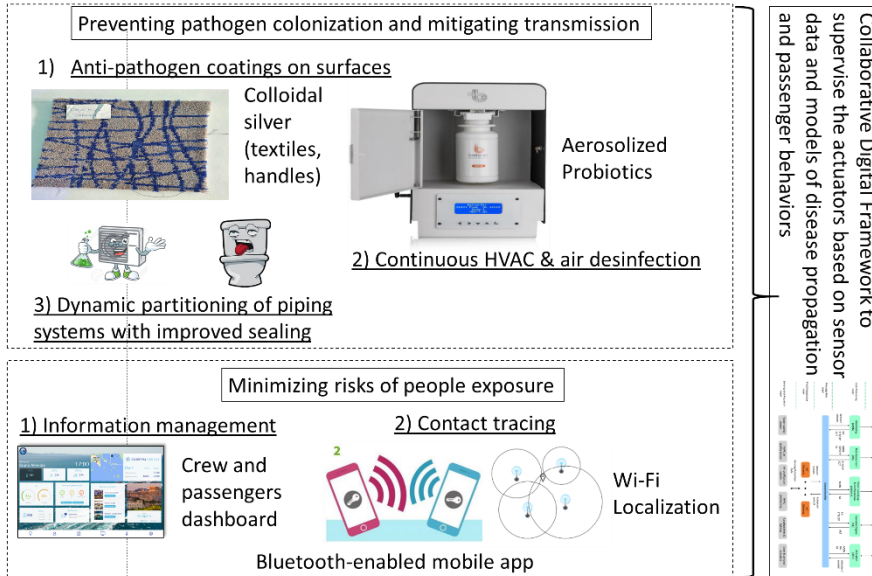
## **HS4U scenarios for S&A**

### **Overview**

Based on the state of the art and the high-level requirements described above and in the related chapters of this book, the following paragraphs detail the scenarios of sensors and actuators that HS4U deems likely to be realized in the near future for outbreak prevention and mitigation aboard cruise ships. The scenarios are illustrated in Figure 2 and Figure 3.



**Fig 2.** Sensors for early detection of outbreaks



**Fig 3.** Actuators for prevention and mitigation of outbreaks. Bluetooth-enabled mobile app - image adapted from [https://edps.europa.eu/data-protection/our-work/publications/techdispatch/techdispatch-12020-contact-tracing-mobile\\_en](https://edps.europa.eu/data-protection/our-work/publications/techdispatch/techdispatch-12020-contact-tracing-mobile_en), last accessed June 29<sup>th</sup>, 2023. Wi-Fi localization - image reproduced from (Mendoza-Silva et al., 2019).

## Sensors for early detection of outbreaks

The ideal sensor system for early detection of outbreaks would allow for each person on board to be continuously monitored anywhere on the ship for symptoms of relevant diseases. The disease should be detected before the person becomes contagious. The method should be selective and able to describe the specific diseases, not just that a person is sick.

The state of the art presented by Lebental (Lebental, n.d.) suggests that the best approach to achieve an outcome where diseases are identified is to equip each person on board with a cheap smart wearable device with the capability to monitor a predefined set of biomarkers and volatile organic compounds (odor) in sweat. There is no doubt that this will be technically feasible in the future, as the elementary building blocks of such a solution are already available, as evidenced in the literature. However, challenging research and development will be required to bring these components together at a commercial level, and even more effort will be required to reduce the cost of the final solution, while the market for such a device remains highly uncertain. Overall, it is estimated that it will be 5 to 10 years before such devices are affordable for the cruise industry.

In the meantime, alternative solutions should be proposed. “Scenario 1” is to have all passengers carry a smart wearable device monitoring vital signs and sound. According to the literature, such a device would be able to identify most respiratory diseases and some of the digestive diseases. This includes diseases that have fever or abnormal heart rate as symptoms. The gap in this approach is the detection of digestive diseases without such symptoms. For such diseases, HS4U proposes to use sound monitoring to detect characteristic sounds indirectly related to digestive diseases, such as gagging sounds or abnormal frequency of toilet flushing. It is important to note that, although there is no literature on such a use of sound monitoring, there are no significant technical limitations either.

It is hypothesized that “Scenario 1” is likely to detect a symptomatic person as soon as the symptoms start. Assuming a suitable communication infrastructure for the devices, the approach is comprehensive as it covers the entire ship and all persons willing to carry the devices. In addition, it addresses most of the symptoms caused by the relevant diseases affecting cruise ships. As requested by cruise industry stakeholders, it has reduced dependencies on the ship itself, provided there is a communications infrastructure in place on the ship (such as Wi-Fi). It can also be positively marketed to the passengers as a health tracker, as such devices are currently gaining traction in the silver economy.

As to accurate disease recognition, there is still a technology gap, as is discussed in detail in (Lebental, n.d.). Results are indeed promising for some respiratory diseases. Beyond that, research is ongoing and at least three to five years are likely to be needed to achieve reliable disease recognition in the general case. This means that in “Scenario 1”, the proposed smart wearable devices will be used as screening tools. People with abnormal symptoms will be referred to the ship’s doctor for further evaluation free of charge. At the ship’s health center, an enhanced point-of-care diagnostics offering, with a sufficient number of rapid tests for the most acute infectious diseases, will allow medical teams to quickly identify the disease and the patient’s needs.

In terms of budget for “Scenario 1”, a smart wearable of sufficient quality can be estimated to cost at least \$30. Therefore, the total budget per 1,000 passengers is estimated at \$30,000. This budget is reasonable on an annual basis, not on a weekly basis, so the devices should be loaned to the passengers, not given away. Assuming 5% of the devices are lost each week, many devices should be completely replaced every 20 weeks, for a total cost of about \$80,000 per year per thousand passengers. In comparison, the cost of rapid diagnostic tests is negligible (<\$1 per unit for bulk orders) and is not included in the cost calculations. It should also be noted that the cost of “Scenario 1” can be reduced by optimizing the choice of devices. There are lower cost devices that may be sufficient for screening purposes; on the other hand, more durable devices (possibly more expensive as well) would allow for a better weekly return rate. Finally, passengers could be encouraged to take better care of the devices and to return them more reliably.

A total cost of \$80,000 per year per 1,000 passengers may be more than cruise ship stakeholders are willing to pay. In addition, some passengers may refuse to carry the devices or carry them only intermittently. This is expected to limit the overall performance of “Scenario 1”.



An alternative solution, "Scenario 2", is proposed based on findings reported in (Almeida et al., n.d.): thermal cameras would be used as fever-screening tools. They would be deployed in the most critical passageways of the ship. The suitable locations for such tools are those where passenger identification is possible, particularly in gangways and restaurants. For illnesses for which fever is not a symptom – mostly digestive disorders – each cabin would be equipped with a sensor monitoring the frequency of toilet flushing. This would have the added benefit of detecting malfunctioning toilets, resulting in improved passenger comfort and water savings. Passengers detected with a fever or abnormal toilet use would be offered the option of either going to the health center or wearing an appropriate smart wearable device (such as defined in "Scenario 1") for a period of time.

In terms of cost, this approach would be significantly less expensive: assuming \$1,000 per camera for 10 cameras with a lifetime of 3 years each; and 1 toilet sensor (<\$5) per cabin for 500 cabins with also lifetime of 3 years, the total estimated cost would be less than \$20,000 per year. However, this approach requires the wiring of hundreds of sensors, which would add significant installation costs (which are not easy to estimate in advance) to the equipment costs and significantly reduce the transferability of the solution from ship to ship. The cost of the fixed sensors must be buffered by a small number (approximately 50 units – 5% of a thousand passenger) of smart wearable devices to monitor symptomatic passengers identified by thermal cameras or by toilet sensors. These devices would be more durable than in "Scenario 1" because they would not be used systematically, but only on a case-by-case basis. Assuming a lifetime of one year in this scenario, the cost would be approximately 15,000\$/year.

In total, "Scenario 2" (monitoring via thermal camera and toilet flushing) is about 50% less expensive than "Scenario 1" (wearable devices for all passengers), but significantly less effective because it detects only two symptoms (fever and abnormal toilet use) and detects these symptoms in specific locations, not throughout the ship. Passengers who are very active even being sick may mostly use public restrooms and not be detected as sick, while passengers with very low activity due to fever may not go to public areas and not be detected as symptomatic. Also, "Scenario 2" is more difficult to market positively to passengers compared to the smart wearable devices that can be used for self-healthcare.

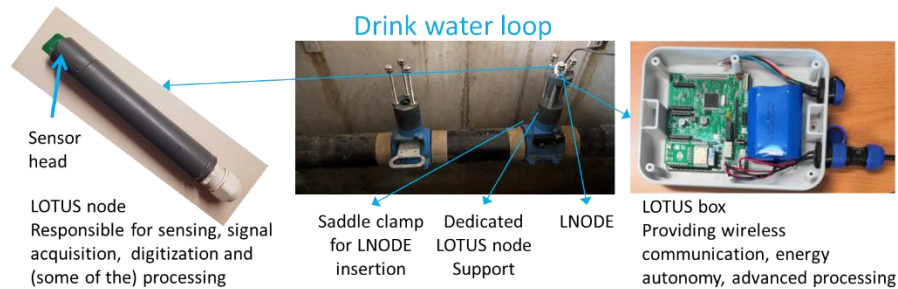
In any case, both scenarios will be limited by the fraction of people who will refuse the use of the technologies described above. Partial coverage of the persons on board means that in the event of an outbreak, patient zero may be missed, which may exacerbate the outbreak. HS4U is conducting a survey of cruise ship passengers to assess the acceptability of scenarios 1 and 2 and to thus determine what fraction of the ship's population could actually be monitored.

To ensure early detection of the outbreak, even in the absence of full coverage of the ship's population, HS4U also proposes to deploy pathogen detection systems throughout the ship's HVAC and sewage systems. A pathogen detection system (PDS) is a real-time, continuous sensor that directly detects the pathogen or its RNA at the point of use. Such a solution would alert the crew that a disease may be circulating on board, ideally well in advance of the actual outbreak, allowing the onboard teams to initiate outbreak prevention and response plans. Depending on the density of sensors deployed, they could also provide information about the

most infected areas, which would then be subject to enhanced disinfection protocols.

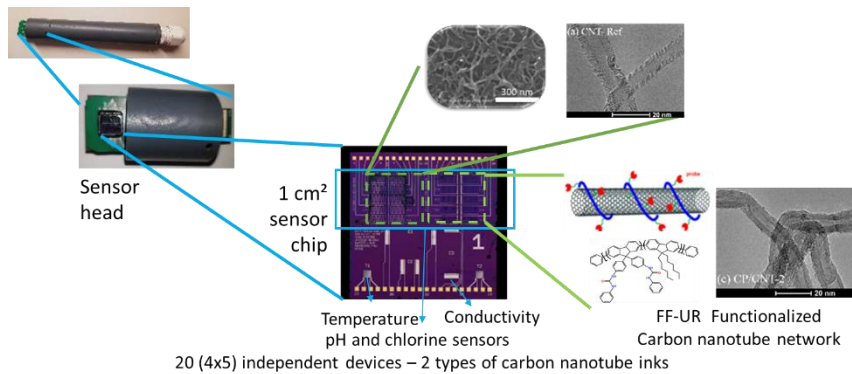
Theoretically, PDS could be deployed in all the cabins, advantageously replacing the two scenarios described above. In practice, PDS are not available in commercial products today, regardless of cost (Krokhine et al., 2021; Pan et al., 2019). As discussed in (Lebental, n.d.), air, urine, and stool sampling systems are available, but automated, real time sample analysis for pathogen detection is not yet commercially available. What is available are solutions for rapid testing of samples by an operator, according to the modalities of point-of-care testing. Commercial availability of automated sampling and pathogen detection is expected to be 3-5 years in the future, at a cost likely to exceed \$1000 per sensor. Therefore, HS4U includes PDS in its scenarios, but in small numbers only: typically, one sensor would be deployed in each air handling unit of the HVAC system. Wastewater-based epidemic monitoring would be realized either on the inlet sampling point of the sewage treatment plant or by integrating further sampling points on the vacuum collecting units or in the black water pipes.

To accelerate the commercial availability of PDS, HS4U also includes the development of PDS for the HVAC system. The technology will be an iteration of the real-time, continuous sensor platform for water quality developed in the LOTUS project<sup>4</sup> by University Gustave Eiffel (Cousin et al., 2022; Perrin and Lebental, 2023) (Figure 4). This sensor platform uses a functionalized carbon nanotube chemistor array for pH and chlorine monitoring (Figure 5). Adding the ability to detect the RNA of pathogens to such a platform is a natural evolution of the technology. It requires functionalization of the carbon nanotubes with the appropriate RNA or DNA strands (Figure 6), as is widely practiced in the literature (Liang et al., 2023). These technologies are not necessarily reversible, which will be the main challenge to be overcome by Université Gustave Eiffel as part of the HS4U consortium.

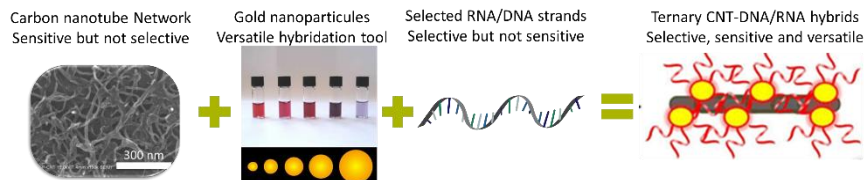


**Fig 4.** LOTUS multiparameter water quality sensor deployed in a drink water loop with wireless capabilities

<sup>4</sup> <https://www.lotus-india.eu/>, last accessed June 11<sup>th</sup>, 2023



**Fig 5.** Principle of operation of the LOTUS sensor: functionalized carbon nanotube chemistor array for pH and chlorine monitoring.



**Fig 6.** Adaptation of the LOTUS sensor for DNA/RNA detection: The carbon nanotubes are functionalized with gold nanoparticles, themselves functionalized by DNA or RNA, forming a ternary hybrid nanomaterial. Gold nanoparticles: copyright Aleksandar Kondinski — kondinski.webs.com. Ternary hybrid: Image reproduced from (Ursu et al., 2017)

## Actuators for prevention and mitigation of outbreaks

For outbreak prevention and mitigation, HS4U's first approach is based on advanced anti-pathogen treatments designed to complement the regular hygiene standards applied by the crew throughout the ship. These solutions are generally designed to inactivate pathogens and are therefore relevant both to prevent the initial contamination by limiting the ability of pathogens to colonize, and to prevent further transmission from index cases by minimizing the density of pathogens. HS4U promotes two subtypes of anti-pathogen treatment described below.

The antipathogen treatment developed by *CNT Labs* uses thin coatings of colloidal silver to inactivate pathogens. More details are provided in (A. Sommariva et al., n.d.). Although various surfaces have shown a high density of pathogens during the COVID-19 crisis, such as sink countertops, handles and floors (Pan et al., 2022), the HS4U approach targets textile surfaces such as carpets, drapes, and upholstery. Indeed, these surfaces are much more difficult and expensive to clean regularly than bathroom fixtures and door handles.

On the other hand, *Ecosense LTD.* proposes a technology based on environmental probiotics (Enviro-Biotics®). It is based on the airborne delivery of aerosolized *Bacillus* spp. spores to indoor surfaces to treat bacterial and fungal pathogens including, but not limited to: *Pseudomonas aeruginosa*, *Staphylococcus aureus* and *Cladosporium sphaerospermum* (Kim et al., 2021). In addition, antiviral activity was demonstrated as Enviro-Biotics® inactivated coronavirus virions (data not published). Spore dispersal is continuous and automatic, ensuring constant replication and reducing human intervention to a minimum. This extends the probiotic coverage to infrequently treated surfaces such as walls, fabrics, furniture and basically the entire indoor environment. A continuous re-application of *Bacillus* supports a constant population of Enviro-Biotics® that treats surface organic contaminants and later acts as a protective layer against any newly introduced pathogens, preventing them from proliferating and colonizing the surface. The dispersal of the probiotics is carried out by localized stand-alone devices or incorporated into a building's HVAC system, thus serving as a holistic solution that treats both all the indoor spaces connected to the HVAC system as well as the HVAC system itself (ducts, filter, air outlets etc.).

In parallel with anti-pathogen treatment, HS4U introduces dynamic control and extensive partitioning of the HVAC and sanitary systems. It is particularly relevant because during the COVID-19 crisis, there was evidence of contamination via the HVAC (Correia et al., 2020; Guo et al., 2021) and the sewage systems (Gormley et al., 2020; Guo et al., 2022; Wang et al., 2022), especially in high-rise buildings. In the post-COVID world, there have been extensive proposals for design optimization of HVAC (Sha et al., 2021; Shamim et al., 2022) and sewage systems (Guo et al., 2022) in order to prevent such transmissions in the future. HVAC optimization has also been proposed by (Mihai and Rusu, 2021) in the specific context of ships.

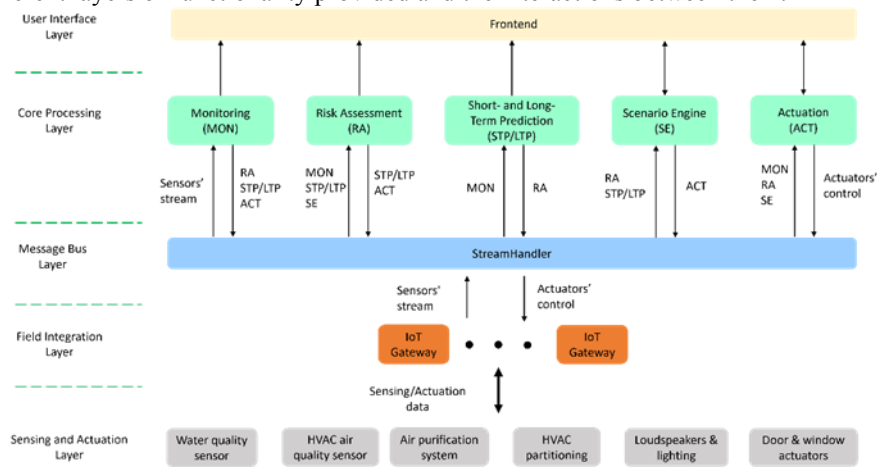
Specifically, in the first phase, Hydrus plans to provide proof of concept that a small part of the ship – to be used as a confinement area - can be completely isolated by partitioning and automating the HVAC and sanitary systems. In a second phase, the possibility of extending this solution to the entire ship will be investigated. Such network partitioning aims to minimize contamination between passengers when a passenger is already contagious but not yet diagnosed and isolated. The work will also include economic considerations. Indeed, automation and optimal control of HVAC and sanitary systems can reduce energy and water usage and thus compensate for the added costs of automation. Let us emphasize that these solutions will be developed to be compatible with both new ships and ship retrofits.

For isolation measures to be effective, contact cases must be properly identified. Contact tracing and/or passenger localization will be necessary if a passenger is found to be ill, especially if their illness is contagious. (Almeida et al., 2023) review the options for achieving this on a cruise ship. This functionality is easily implemented for scenario 1 at no additional cost. For scenario 2 however, another sensor infrastructure may be required. Alternatively, passengers may be asked to activate contact tracking on their cell phones. Interestingly, most contact tracking applications operate without the exchange of personal data, which could increase the acceptability of contact tracking to passengers.

Finally, information management is critical in the event of an outbreak. The HS4U framework includes dashboards for crew and passengers as well as tools for reporting to the relevant authorities. To enable crew or medical teams to easily communicate outbreak-related information to passengers, dashboards will be made available on mobile phones and on the various displays on board (in cabins and public areas). In regular operation (in the absence of an outbreak), they may also include personalized passenger information collected by the various sensors, similar to the dashboards proposed by activity trackers (e.g. activity level, health status, etc.). To streamline the crew efforts during an outbreak, crew dashboards available on tablets and smart phones will facilitate the transfer of information between different teams and advise the crew on actions to be taken.

## Digital platform for S&A data processing

To facilitate the use of S&A to prevent and mitigate outbreaks in an efficient, automated, and easily reconfigurable manner, HS4U will design and develop a Collaborative Digital Framework (CDF) that processes the sensor data and combines it with models of passenger behavior and disease propagation to suggest actions to be taken. Figure 7 presents a high-level view of the CDF, showing the different layers of functionality provided and the interactions between them.



**Fig. 7.** High-level view of the interaction between S&A and the CDF components

The Sensing and Actuation Layer consists of all the S&A systems that will be either developed and/or upgraded in HS4U (e.g., pathogen detection systems, air purification systems, smart wearable devices) or already exist on ships (e.g., loudspeakers and other alarm systems, door/window actuators, etc.).

The Field Integration Layer consists of IoT gateways that provide the interoperability framework connecting the Sensing and Actuation Layer with the upper lay-

ers of the CDF. To achieve this, the IoT gateways will interact directly with all the sensors and actuators installed in the different compartments of the ship, and will host appropriate software connectors for forwarding sensor data and actuator control commands to/from the Message Bus Layer.

The Message Bus Layer consists of the StreamHandler platform provided by Netcompany-Intrasoft. StreamHandler is a distributed event-driven streaming platform that will be deployed in a horizontally scalable manner, addressing challenging in load, fault tolerance and security requirements. StreamHandler uses Apache Kafka<sup>5</sup> and will provide a common data model and a set of interfaces that allow loose coupling between the interacting components following the publish/subscribe messaging pattern.

The Core Processing Layer consists of different groups of components (indicated in Figure 7 by green colored rectangles) that perform specific functionalities related to the models that will be developed by the HS4U partners (risk assessment, passenger behavior, and disease propagation). This layer will follow a microservices architecture, where the various software components that make up the different sets of functionalities will be deployed in a containerized form (e.g., Docker), supported by a Kubernetes<sup>6</sup> instance for their management. The interactions between all these components will also take place via the Message Bus Layer.

Below is a brief description of the different component groups and their interactions.

- **Monitoring (MON):** In MON, the platform receives input from all the sensing devices and harmonizes the observations into a readable form. The main service of the MON components is to monitor and measure the status of ship systems, pathogens in air, water and other locations, and the passenger conditions (e.g., fever). These measurements are then used by other components of the platform to trigger specific actions.
- **Risk Assessment (RA):** In RA, measurements are categorized based on severity (risk assessment models, e.g., speed of disease spread, severity, passenger demographics). An ontology representation of the sensor measurements steers the whole process. If a high severity event is detected, an emergency scenario should be activated. RA models fall into two categories: a) strategic models for known pathogens, which address the entire ship, and b) tactical models for mitigation and response measures (e.g., what is the risk of quarantining passengers in one room instead of another). Essentially, the RA components receive thresholds and severity levels from the STP/LTP (see below) that guide the process to trigger actions and notifications to responsible crew members. In addition, prediction on the platform may not only be related to the emergency scenarios, but could also notify the crew of potentially dan-

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<sup>5</sup> <https://kafka.apache.org/>

<sup>6</sup> <https://kubernetes.io>

gerous situations (e.g., a healthy individual is about to enter an infested area).

- **Short and Long-term Prediction (STP/LTP):** The STP/LTP is where the full lifecycle of the modeling process is implemented. Models for different objectives are executed in the form of containerized instances that provide valuable outputs to the other components. To implement the strategic and tactical risk assessment, the required predictive model includes pedestrian analytics, disease propagation, resource allocation, and other supporting models.
- **Scenario Engine (SE):** Through the SE, the platform implements a user interface (UI) board that is capable of creating a schematic scenario indicating actionable “if-this-then-that” type of plans. These plans are created per ship by the crew and ship owners. In addition, scenarios/plans are reviewed in real time based on forecasts and tactical risk assessment in collaboration with STP/LTP and RA. The platform communicates the tactical risk assessment to the crew so that they can make more informed decisions. The decisions are co-created with the platform: the platform provides a simulation environment where the crew can virtually test decisions and actions (“what-ifs”), resulting in a new risk assessment.
- **Actuation (ACT):** Through the ACT, the platform will assist crew members in carrying out a specific plan. This is done by automatically enabling available actuators on the ship, e.g., closing doors, switching off lights to darken rooms and deter passengers from entering, and activating ventilation.

Finally, the User Interface Layer constitutes the CDF’s frontend to the different kinds of end users (e.g., captain, crew, passenger, system administrator). In particular, depending on the user’s needs and access rights, the frontend will visualize various types of information coming from the components of the Core Processing Layer (e.g., through suitable menus, dashboards and notifications) and also provide an interface for sending specific commands or requests.

## Conclusion and prospects

This chapter reports on the progress made by HS4U in defining a set of sensor and actuator solutions suitable for use on cruise ships to prevent and mitigate outbreaks. After presenting the high-level requirements of the solutions, including business and integration constraints, the paper addresses the state of the art of sensors and actuators for outbreak management in and outside the naval context: technologies for symptom detection, disease recognition, and passenger localization are discussed, as well as approaches for surface, air and duct purification, and for communication between the crew, the public, and authorities. Coupling the re-

quirements with the state of the art allows to describe several feasible scenarios for the deployment of sensors and actuators aboard a cruise ship. The architecture of a digital platform capable of utilizing the proposed sensors and actuators to assist the crew in preventing and mitigating an outbreak is also described. While the work reported here has been essential to allow the consortium to enter the low-level requirements and design phase of its solutions, it may also have a broader impact: on the one hand, it aims to familiarize the cruise ship stakeholders with the technologies offered by the Internet of Things for health-related matters and to consider their adoption in the near future; on the other hand, it may contribute to the development of future regulations regarding outbreak management by competent authorities.

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