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A COVID-19 outbreak on board ship: Analysis of the sociotechnical system of epidemiological management in the French Navy

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ABSTRACT

In late 2019, an epidemic of SARS-CoV-2 broke out in central China. Within a few months, this new virus had spread right across the globe, officially being classified as a pandemic on 11 March 2020. In France, which was also being affected by the virus, the government applied specific epidemiological management strategies and introduced unprecedented public health measures. This article describes the outbreak management system that was applied within the French military and, more specifically, analyzes an outbreak of COVID-19 that occurred on board a nuclear aircraft carrier. We applied the AcciMap systemic analysis approach to understand the course of events that led to the outbreak and identify the relevant human and organizational failures. Results highlight causal factors at several levels of the outbreak management system. They reveal problems with the benchmarks used for diagnosis and decision-making, and underscore the importance of good communication between different levels. We discuss ways of improving epidemiological management in military context.

1. Introduction

In December 2019, several cases of pneumonia were recorded in the Chinese city of Wuhan, caused by a then unknown virus. On 7 January 2020, after alerting the World Health Organization (WHO), the Chinese authorities confirmed the emergence of a new disease, which was officially named COVID-19 by the WHO on 11 February. The latter was caused by a virus belonging to the coronavirus family, referred to as SARS-CoV-2 to differentiate it from the SARS-CoV virus that was responsible for the SARS epidemic in 2002–2003. The epidemic gradually spread beyond China and affected a growing number of countries, taking advantage of international travel. It eventually paralyzed almost 200 countries, thereby threatening the global economy. On 11 March 2020, the WHO officially declared COVID-19 to be a pandemic. France had already had several confirmed cases by 30 January. The virus soon spread rapidly throughout the country, which had officially recorded 145,555 cases, including 28,530 deaths, by 27 May 2020. The scale of the health crisis prompted the government to implement drastic measures and mobilized the entire hospital system.

The French Ministry of Armed Forces joined the Ministry of Health in the fight against COVID-19. The Armed Forces Health Service (SSA) applied the strategy defined by the Ministry of Health to combat, limit and curb the transmission of the virus in all branches of the armed forces. To ensure that the latter could continue their missions, additional measures were adopted to accelerate the epidemiological investigations carried out among the military and civilian personnel affected by the disease. This activity was mainly undertaken by the Center for Epidemiology and Public Health of the Armed Forces (CESPA), which is affiliated to the SSA. CESPA’s main purpose is to participate in the epidemiological surveillance of French military forces, whether they are stationed in mainland France or abroad. Its objective is to identify the occurrence of an epidemic in order to manage it and implement public health actions designed to bring it under control as quickly and as far as possible. Given the spread of the virus within both civilian and military populations, the CESPA team soon had to concentrate all their energy on managing the COVID-19 epidemic. On 7 April 2020, the Ministry of Armed Forces was informed of a COVID-19 outbreak within the French Carrier Strike Group (GAN), then on operational deployment.

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CESPA was ordered to participate in the management of the situation and to conduct an epidemiological investigation. This outbreak, detected following a stopover in Brest, mainly affected the Charles de Gaulle nuclear aircraft carrier (PAN CDG), where there were more than 1000 confirmed cases. Faced with an outbreak on such a scale, the authorities had no choice but to curtail the deployment and organize the GAN’s immediate return. Although no deaths were reported, this outbreak had serious financial and operational consequences for the French Navy.

It therefore seems important to investigate the possible malfunctions or failures that led to this outbreak. We examined the sequence of events leading up to the outbreak on board the aircraft carrier, in order to determine the human and organizational factors involved, with a view to improving them. Social science research on disasters and accidents leading up to the outbreak on board the aircraft carrier, in order to or failures that led to this outbreak. We examined the sequence of events has emphasized the importance of considering the fundamentally sys serious financial and operational consequences for the French Navy. Waterson, 2016). When critical events occur, systems allocate their re liable to develop even in the normal course of operations (Nayak and ment capacity and increases the risk of incidents. Epidemiological management is a command and control system based on a fixed and dynamic and complex nature of these systems is such that incidents are unexpected and uncontrolled interactions between the different levels of a sociotechnical system. According to Underwood and Watson, 2014), incidents arise from unexpected and uncontrolled interactions between the different levels of a sociotechnical system. Analysis of the sequence of events leading to an epidemic does indeed reveal a complex interaction between the levels of such systems, which may include the work environment, staff, management, business, regulators, and government (Pennington, 2009). The dynamic and complex nature of these systems is such that incidents are liable to develop even in the normal course of operations (Nayak and Watson, 2016). When critical events occur, systems allocate their re sources to coordination and adaptation, which reduces their manage ment capacity and increases the risk of incidents. Epidemiological management is a command and control system based on a fixed and linear structure that may rapidly start to show cracks in a crisis situation. For Celik and Corbacioglu (2016), a system that relies on fixed procedures may find it hard to adapt to a new situation by reorganizing staff and resources. External crisis-related influences (e.g., political, financial and media factors) are a source of instability at every level. Maintaining control is therefore a process that involves the entire sociotechnical system (Svedung and Rasmussen, 2002).

Rasmussen (1997) considered that every level of the system should be involved in safety management, by controlling the processes that are carried out through laws, regulations and instructions. Through their various decisions and actions, all actors and organizations can shape “a causal path through the landscape along which an accidental course of events sooner or later may be released” (Rasmussen and Svedung, 2000, p. 17). Rasmussen broke sociotechnical systems down into their tech nical, human and organizational dimensions, and modeled them (see Fig. 1) as different strata ranging from legislators to organizations and their functioning (Ili Ciocci, 2012). For systems to operate safely, de cisions made at higher levels must be promulgated and reflected in de cisions and actions occurring at lower levels. By the same token, information must move from lower levels up the hierarchy to inform the actors who make decisions at higher levels (Waterson et al., 2017). As in risk management, the occurrence of an incident involves every single level. It is therefore important to conduct an overall analysis of that incident. Systems should be studied as whole entities rather than being considered in their separate parts. To this end, Rasmussen (1997) laid the foundations for a systemic approach that aims to represent the complex interaction between the decisions and actions leading to an incident: the AcciMap method. This method makes it possible to iden tify, and represent in graphic form, the causal factors and the events that led to an incident at all the levels of the system that were impacted. Unlike analysis methodologies intended to apportion responsibility, this model seeks to produce a more global representation than the traditional causal tree, based on information about the parameters contributing to the incident and the conditions under which it took place (Lim et al., 2002). “As is the case with the causal tree normally used to represent the findings from post-hoc accident analysis, the basic AcciMap is developed from analysis of one particular accident case” (Rasmussen and Svedung, 2000, p. 20). Nevertheless, this approach focuses not only on the direct sequence of events and actions leading to the incident, but also on the preconditions that may have influenced or conditioned its occurrence. It therefore also aims to identify the factors for optimizing the operation and safety of the system.

2. Theoretical background

Epidemiological management consists in continuously collecting, analyzing and interpreting sets of medical data in order to detect potential epidemics and, if necessary, trigger the immediate implementa tion of control measures. This sociotechnical organization relies on a group of medical experts from various complementary fields who are trained in the management of epidemic risk situations. These complex and dynamic situations have many different components that can in fluence each other but also change independently. Epidemiological management is therefore carried out in a context of uncertainty about the facts and possible developments, where changes can rapidly take place in space and time, and many organizational and technical con straints need to be taken into account. In a routine context, experts can rely on a set of procedures that allow them to manage epidemic alerts quickly and efficiently, but these procedures are not always sufficient when it comes to resolving certain acute or unexpected situations. Epidemic alerts can have differing degrees of complexity and criticality, and even lead to crisis situations. A crisis can be defined as a generally unexpected event, the consequences of which develop rapidly. It is associated with substantial risks, and can rapidly overwhelm existing resources (i.e., procedures, actions, and personnel) (Rogalski, 2004). Pressures mount, undermining the entire sociotechnical system and hampering the management of the crisis, with operators losing control. The conditions are then ripe for an incident to emerge.

According to Underwood and Watson (2014), incidents arise from unexpected and uncontrolled interactions between the different levels of a sociotechnical system. Analysis of the sequence of events leading to an epidemic does indeed reveal a complex interaction between the levels of such systems, which may include the work environment, staff, manage ment, business, regulators, and government (Pennington, 2009). The dynamic and complex nature of these systems is such that incidents are liable to develop even in the normal course of operations (Nayak and Watson, 2016). When critical events occur, systems allocate their re sources to coordination and adaptation, which reduces their manage ment capacity and increases the risk of incidents. Epidemiological management is a command and control system based on a fixed and linear structure that may rapidly start to show cracks in a crisis situation. For Celik and Corbacioglu (2016), a system that relies on fixed 3. Methodology

3.1. Data collection

To obtain a set of precise data on the timecourse of events leading to the COVID outbreak on board the aircraft carrier, we opted for the so-called participant observation method. According to Bogdan and Taylor (1975), participant observation is a process of field study, characterized by a period of sustained social interaction between researchers and participants. During this period, observers totally immerse themselves in the lives of their targets, in order to share their experiences, carry out exhaustive data collection, and grasp all the subtleties (Soulié, 2007). As in-house CESPA researchers, we had the opportunity to come into direct contact with some of the actors, and gain access to information that is usually difficult to obtain. This involved taking advantage of our role to observe the situation from the inside. To this end, the purpose of our study was made public to CESPA staff from the very outset. As parti cipating observers (Gold, 1958), we gained access to a great diversity of information, whilst respecting the confidential and ethical nature of ergonomic psychology. We were thus able to compile a timeline retracing the intervention by CESPA operators. This involved noting down all the observations made by the CESPA teams in charge of investigating the epidemic. Participating in the activity of the operators also allowed us to retrieve the documentation we needed to gain a precise understanding of the situation. Our analysis was mainly...
Fig. 1. The sociotechnical system involved in risk management (Svedung and Rasmussen, 2002).
conducted on a set of public documents, such as the written transcript of a speech made by the Armed Forces Minister on 17 April 2020 (Parly, 2020), the general public summary of the investigations relating to the COVID-19 outbreak on the aircraft carrier, and the report of the epidemiological investigation carried out by CESPA. Other internal documents (e.g., logbook, minutes of meetings, daily situation reports) were used to guide our understanding and clarify the chronology of events. These were studied with scrupulous respect for professional secrecy.

3.2. The AcciMap method

To take into account the whole sociotechnical context in which the outbreak occurred on board the aircraft carrier, we chose to analyze the data we collected using the AcciMap method. Developed by Rasmussen in 1997, then Svedung and Rasmussen in 2000 and 2002, this method makes it possible to build a graphic representation of the different causes of the incident at every level, showing their distance from the result (Branford et al., 2009). Providing both a horizontal description of the sequence of events and a vertical description of the factors that had impacted the course of the incident (Morel, 2007), its purpose is to highlight the events, decisions, and actions that caused the sociotechnical system to lose control (Branford et al., 2009), and identify any corrections and improvements that can be made at the different levels of the system, in terms of laws, regulations, instructions and procedures:

1. Government: safety legislation developed to control professional procedures;
2. Regulatory and expert bodies: application of occupational safety legislation;
3. Local government: company policy and administrative application of regulations;
4. Technical and operational management: specification and supervision of staff activities with reference to company rules and policies;
5. Physical processes and human activities: operators responsible for following their managers’ instructions;
6. Equipment and surroundings: premises and materials made available to operators to carry out their activities in compliance with company rules.

The bottom level (Level 6) corresponds to the contextual elements, physical characteristics and topography of the places configuring the

![AcciMap Diagram](image-url)

**Fig. 2.** An approach to structure an “AcciMap” and a proposed legend of standardize symbols (Rasmussen and Svedung, 2000).
environment of the incident, Level 5 to the events and causal relationships directly involved in the unfolding of the incident, and Levels 4, 3, 2, and 1 to all the human actors whose decisions influenced the conditions leading to the incident.

Rasmussen also designed a more general modeling framework, the ActorMap model, which provides an overview of the various components of the system under scrutiny, as well as the interactions between them. This type of graph is intended to allow a better understanding of the flow of interactions between the different decision-making bodies that can lead to incidents. Although Rasmussen’s approach was originally developed to analyze industrial accidents, it can be reconfigured and adapted (following the author’s recommendations) to extend its use. This flexibility allows the approach to be applied to other disciplines, such as medicine and epidemiology. Several epidemics have already been studied using the AcciMap method, including the *Clostridium difficile* outbreaks in the Maidstone and Tunbridge Wells NHS Trust in England (Waterson, 2009), and the *Escherichia coli* O157:H7 outbreaks in Scotland in 1996 and Wales in 2005 (Nuyak and Waterson, 2016).

### 3.3. Analysis

Our AcciMap model was designed according to Rasmussen and Svedung (2000)’s guidelines. These authors proposed using a graphical code to clarify the representation (see Fig. 2). The influencing factors (decisions, actions, events) are modeled as interconnected rectangles. However, unlike usual causal representations, an AcciMap diagram not only includes the events and actions that were directly related to the occurrence of an incident, but also represents all the players in the sociotechnical system whose decisions influenced the conditions leading to the incident (Svedung and Rasmussen, 2002). The links shown in the model therefore represent influences without necessarily implying a causal relationship. Factors that are directly linked are modeled as contiguous rectangles. The graph also features preconditions and priorities that are useful for understanding and contextualizing the unfolding of events. These items, which were not subject to analysis, are represented by rounded rectangles, to distinguish them from other factors. We chose to add a timeline below the diagram to give a more precise indication of the timing of the facts.

To conduct our analysis using the AcciMap method, we first focused on the aircraft carrier’s epidemiological management system. Examining the usual functioning of the system allowed us to identify the decisions and interactions that took place within and among its components. This preliminary research led us to produce an ActorMap representing the different actors and entities that made up the system, as well as the communication flows between them. All the documents and reports we had retrieved were then studied in detail. The information we extracted was analyzed in order to reconstruct the sequence of events that led to the COVID-19 outbreak on board the aircraft carrier (see Table 2). The AcciMap model was then constructed, following the steps set out in Table 1, and validated by the CESPA experts who had been most closely involved in the management and subsequent investigation of the epidemic.

### Table 1

| Step | Details |
|------|---------|
| 1    | Identification of the starting point for analyzing the outbreak. |
| 2    | Identification of the human actors at each level of the system who were involved in the occurrence and management of the incident (see Table 2 and Fig. 3). |
| 3    | Identification of the external factors and decisions involved in the incident. |
| 4    | Identification of the intermediate consequences and final outcome. |
| 5    | Arrangement of the elements we had identified according to their level and timing. |
| 6    | Insertion of links between these elements. |
| 7    | Addition of a timeline indicating the chronology of the events. |

### 4. Results

#### 4.1. Usual outbreak surveillance and management process on the aircraft carrier

We began our analysis by identifying the entities and human actors that made up the aircraft carrier’s epidemiological management system. After describing the functions performed by the various actors, we identified their level within the system and the connections between them. The apex of the systemic structure is divided into two parts: civilian and military. On the civilian side, the Ministry of Solidarity and Health is responsible for implementing government policy in the areas of social affairs, public health, and social protection. To carry out its public health missions, the Ministry relies on the Directorate of Health (Level 1), which draws up public health policy and contributes to its implementation, and on centers of expertise (Level 2), such as the National Health Agency, which specializes in epidemiological surveillance. On the military side, health management is the responsibility of the SSA, which is answerable to the Ministry of Armed Forces (Level 1). The SSA guarantees medical and surgical support for the French armed forces, both in metropolitan France and in overseas theaters of operation. As such, it contributes to public health policy, in collaboration with the Directorate of Health, through CESPA (Level 2). The latter is in charge of the epidemiological surveillance of the entire French military population, and helps to implement and disseminate the SSA’s recommendations to the forces’ various medical services. As such, it is the first point of contact for the army’s services and medical managers (Levels 3 and 4) if there is an epidemic risk or actual outbreak.

Level 3 of the epidemiological management system includes the Chieftaincy of the Health Service for the Naval Task Force, which is responsible for the preparation, support and technical control of on-board medical services. It is under the technical authority of the SSA and the functional authority of the squadron vice-admiral of the Naval Action Force (Level 3). Level 4 is occupied by the chief medical officer (answerable to the Chieftaincy of the Health Service) and the commander of the aircraft carrier (answerable to the squadron vice-admiral). The chief medical officer is responsible for the medical team on board the aircraft carrier, which generally consists of three doctors, eight nurses and a medical secretary. It can be reinforced by surgical staff on request. The commander has administrative responsibilities for carrier personnel, equipment and finances. Together, the chief medical officer and the commander are responsible for taking medical decisions regarding the crew, with input from their respective chains of command. The carrier’s medical team and crew are located at Level 5.

Thus, the first three levels of the system concern government agencies and centers of health expertise, overseeing civilian and military epidemiological management. The next two levels correspond to the different hierarchical and functional strata within the aircraft carrier. We therefore observe a geographical separation between the supervisory levels (metropolitan France) and the other levels of the system (on board the ship). Despite this separation, we noted a need for the exchange of information between the two. The assessment of communication links also revealed the involvement of civilian bodies with oversight of the military’s decision-making strategies concerning the epidemiological surveillance of COVID-19 within the armed forces. This first phase of analysis allowed us to produce an ActorMap showing the communication links between the components of the system under scrutiny (see Fig. 3).

#### 4.2. Course of events leading to the COVID-19 outbreak on the aircraft carrier

The timing of events leading to the COVID-19 outbreak on board the aircraft carrier is summarized in Table 2. On 21 January 2020, before the threat of COVID-19 had reached France, the aircraft carrier, accompanied by other ships of the French Navy, sailed from Toulon as
part of a mission that was due to last until 23 April 2020. The first cases of the disease began to be recorded in France shortly afterwards. On 29 February, given the increasing spread of the virus, the French Government announced the transition to Stage 2 of the epidemic. The carrier’s commander, warned of the situation in mainland France, evaluated the risk of the crew being contaminated and decided to apply the health measures recommended by the SSA. Confident in his action plan and in his management capacity, he chose to go ahead with a planned stopover in Brest on 13–16 March for technical needs and a change of crew. Special measures were taken during the stopover to avoid the risks associated with the health situation in mainland France. The transition to Stage 3 of the epidemic, announced on 14 March, prompted the commander of the aircraft carrier to put in place strict measures on leaving Brest. Over the following 2 weeks, as the aircraft carrier continued its mission in the North Sea, a steady stream of sailors (approx. 12) arrived in the ship’s hospital with respiratory symptoms. These patients were not identified as possible cases of COVID-19 by the medical personnel, who instead attributed their symptoms to their working conditions, as some of them were working on the flight deck in strong winds and temperatures approaching 0 °C. On 30 March, during a stopover in Denmark, a dozen sailors went ashore. The same day, the commander, with the go-ahead of the medical service, which still believed that the disease was not present on board, decided to relax the health measures and agreed to allow a concert by the carrier’s amateur orchestra to be held in the ship’s aircraft hangar. The first signals of the disease came on 5 April, with an increase in the number of consultations and hospitalizations for respiratory syndromes. Possible cases were processed in the ship’s infirmary and then placed in isolation in the forward sections of the ship. On the same day, one of the sailors who had gone ashore in Denmark sent word to the aircraft carrier that he had tested positive. The commander was then made aware of the presence of the virus within the aircraft carrier. He ordered the resumption of restrictive health measures, but decided to continue the carrier’s mission off the northern end of the Bay of Biscay. Despite the health measures, the epidemic continued to grow, with more than 30 sailors showing symptoms of the disease. On 7 April, faced with an increase in the number of possible cases, the commander decided to alert the military authorities and the Ministry of Armed Forces. The Minister immediately halted the mission and ordered the aircraft carrier to return to Toulon, so that the crew could receive appropriate medical care. A team of epidemiologists arrived on board the aircraft carrier on 8 April. Samples were taken, biologically confirmed the presence of the

Table 2
Course of events leading to COVID-19 outbreak on board the aircraft carrier.

| Date       | Events                                                                 |
|------------|------------------------------------------------------------------------|
| 29 February 2020 | French Government announces transition to Stage 2 of COVID-19 outbreak. |
| 13 March 2020   | Aircraft carrier stops over in Brest.                                  |
| 14 March 2020   | French Government announces transition to Stage 3 of COVID-19 outbreak. |
| 16 March 2020   | Aircraft carrier sails from Brest.                                     |
| 16–30 March 2020 | Constant stream of sailors to infirmary with respiratory infection syndromes. |
| 30 March 2020   | A dozen sailors disembark in Denmark.                                   |
| 5 April 2020    | Large number of sailors go to infirmary with respiratory infection syndromes. |
| 7 April 2020    | Commander of aircraft carrier alerts military authorities and Minister of Armed Forces. |
| 8 April 2020    | TSSA team sent on board aircraft carrier.                              |
| 13 April 2020   | Aircraft carrier arrives in Toulon.                                    |
virus in 50 sick sailors. The initial assumption was that the virus had arrived on board during the stopover in Brest. COVID spread so rapidly that it overwhelmed the ship’s logistical organization, with its hospital and isolation facilities full to capacity. On their arrival in Toulon on 13 April, after biological tests, all members of the ship who were diagnosed as having COVID-19, were placed in quarantine on shore. By the end of the epidemic, a total of 1148 seafarers had been classified as confirmed cases. Although no deaths were reported, two sailors had a severe pulmonary form requiring intensive care treatment. Once the situation had stabilized, the Ministry of Armed Forces ordered the armed forces inspectorate, the naval inspectorate and the SSA inspectorate to carry out investigations in order to understand and learn from this event. CESPA was officially appointed on 19 April to conduct the epidemiological investigation.

4.3. AcciMap analysis results

The AcciMap model based on the final analysis is shown in Figs. 4–6. Although entities at the third level of the epidemiological management system may have been involved in the course of the outbreak, they are not explicitly mentioned in the documents we used in our study. For this reason, although Level 3 was present in the the ActorMap, it does not

![AcciMap diagram of the COVID-19 outbreak on the aircraft carrier (Part 1).](image-url)
appear in our AcciMap model. The announcement of the transition to Stage 2 of the epidemic in France served as the starting point for our analysis of the events that led to the outbreak, as it led to the publication of a series of recommendations on which the SSA exclusively relied to enact its epidemiological surveillance strategies. These included case definition criteria, diagnostic methods (biological analyses), and criteria for accessing these analyses, restricting their use to persons identified as possible cases. The carrier’s commander and medical team relied on these guidelines to develop their course of action. This resulted in health checks of all personnel on board and, if necessary, medical monitoring to detect the emergence of evocative symptoms based on the definitions that had been communicated to them. In the absence of biological diagnostic testing facilities on board, the medical team had to rely on the possible case definition to diagnose the presence of COVID-19 cases in the crew. However, the clinical criteria taken into consideration and included in the definition were not enough for the on-board medical team to detect the presence of the disease among crew members. Health and safety measures within the ship had been strengthened as the situation in metropolitan France changed, and procedures had been updated. In particular, during the stopover in Brest, no on-board visits had been allowed, seamen who went ashore were forbidden to go to the clusters that had been identified at that time, and all personnel joining the ship had to complete an exposure risk assessment questionnaire.

The transition to Stage 3 of the epidemic on French territory during this stopover led the commander to establish rigorous distancing measures, with no gatherings, less frequent briefings, new rules for playing...
In the 14 days following the stopover, the health authorities announced the discovery of two new characteristic clinical criteria: anosmia and ageusia. However, although armed forces physicians were informed of these criteria on 27 March, the latter were not included in the possible case definition, and do not seem to have come to the attention of the onboard medical team. Medical personnel therefore continued to use the clinical criteria for acute respiratory syndromes and fever, set out in the possible case definition, to detect the virus. However, the primary function of these criteria was to standardize epidemiological reporting, and they were not enough to allow a diagnosis of the disease. Although there was a moderate but constant flow of sailors to the infirmary presenting with respiratory symptoms, the medical team, focusing on the instructions given by the authorities and convinced of their diagnosis, failed to detect the signals of virus spread among the crew. Believing that the disease was not present on board the ship, and aware of the impact of the restrictive health measures on crew morale, the commander decided to relax these measures from 30 March. A concert was held that same day in the aircraft hangar, bringing together 532 sailors, some of whom were subsequently identified by epidemiological investigators as carrying the virus on that date.

The spread of the disease then accelerated until 5 April, when the increased flow of patients admitted to the infirmary for respiratory infections began to raise suspicions. It was only when one of the sailors who had disembarked in Denmark reported that he had tested positive that there was a real awareness that there might be an established
COVID-19 outbreak on board. The commander ordered the immediate resumption of strict health and safety measures, together with the isolation of all possible cases. However, he only inform his superiors 2 days later, thus delaying intervention by the authorities. Despite the arrival of reinforcements from the SSA, the scale of the outbreak was such that the ship’s logistical organization was rapidly overwhelmed, with insufficient technical, operational and material resources. The authorities then decided to curtail the aircraft carrier’s mission.

The AcciMap diagram and the analysis of the decisions and influencing factors that led to the outbreak (see Table 3) show that the epidemic on board the aircraft carrier cannot be attributed to individual decisions, but resulted from an accumulation of multiple factors that interacted at different levels of the sociotechnical system. Although the model focused on two main factors, located at Level 4, analysis revealed the impact of other precursor factors across Levels 2–5 of the system. Analysis also revealed a communication failure between Level 2 and Levels 4 and 5. Better exchanges between the SSA’s expert bodies and the medical service on board the aircraft carrier would have doubtless led to earlier detection of the virus among the crew. Likewise, more rapid reporting by the ship’s commander would have enabled the authorities to intervene slightly earlier.

5. Discussion

Aircraft carriers are aeronautical platforms with continuous personnel movements, both between ships and with land. There were therefore numerous opportunities for contamination from the very start of the mission. The epidemiological investigation carried out by CESPA traced the dynamics of the epidemic and concluded that the virus had first arrived on the ship as early as late February. Although the origin of the contamination could not be precisely determined, the first cases were confirmed a posteriori, based on the presence of anosmia and ageusia, which are now recognized as more disease-specific symptoms. The epidemiological investigation therefore showed that the Brest stopover should not be regarded as triggering the epidemic on board. Nevertheless, it may have allowed the virus to be reintroduced, and with the subsequent easing of measures on 30 March, the disease quickly spread among the crew. The investigation highlighted two days of high spread, on 31 March and 1 April, immediately after the relaxation of health and safety measures.

The systemic analysis of the outbreak showed that the diagnostic difficulties encountered by the on-board medical team had an impact on the commander’s decision to relax the restrictive measures. The late detection of the epidemiological signal can therefore be regarded as an indirect cause of the spread of the epidemic within the crew. However, the investigation revealed that in the absence of recommendations on how to use the diagnostic tools available on board, the medical service had to rely solely on the criteria defined by Public Health France, and communicated by the SSA to detect possible cases. These clinical criteria were acute respiratory infection and fever, to which was added a notion of exposure to a risk zone, or contact with a possible or confirmed case. However, the investigation highlighted the very low sensitivity and specificity of these criteria for the detection of the disease within the crew, as the latter were mainly young and did not develop severe clinical forms. The first definitions used to detect cases were based on information provided in the scientific literature, and more disease-specific symptoms like anosmia and ageusia were only brought to the attention of French clinicians at quite a late stage. Moreover, although these additional detection criteria were made public by the Directorate of Health on 22 March, this news does not appear to have reached the medical service of the aircraft carrier. The epidemiological investigation clearly showed that the use of these two clinical criteria for screening possible cases would undoubtedly have made it possible to detect the epidemiological signal as early as 23 March. There was clearly a dysfunction in the dissemination of information and recommendations, leading to gaps in benchmarks for decision-making.

The investigations carried out by the inspectors of the French Navy and Armed Forces highlighted the factors that led to the aircraft carrier losing control of the epidemic. The carrier’s commander, who was utterly confident in his health analysis and epidemiological management capacity, preferred to deal with the situation internally before informing the authorities of the suspected outbreak on board the ship. It was only when the health situation reached epidemic proportions that the commander decided to alert his superiors. The operational and technical organization of the aircraft carrier was soon overwhelmed by the spread of the epidemic, as its hospital capacity was saturated, forcing it to group patients in precarious conditions until their arrival in Toulon. These investigations therefore revealed the limitations of an operation that was too isolated in this context.

Analysis of the outbreak on board the aircraft carrier made it possible to identify problem areas throughout the sociotechnical structure responsible for epidemiological management, and to determine which factors might be improved. The diagnostic difficulties encountered by the medical personnel of the aircraft carrier revealed a need to consolidate the health strategies implemented when a new form of disease emerges, in order to be able to detect early symptoms and conduct a more effective testing campaign. One solution would be to set up a health watch, to monitor all relevant scientific publications, in order to adjust the procedures to be followed at the different levels of medical intervention as quickly as possible. This monitoring would provide military doctors with reliable, up-to-date knowledge, in order to ensure the most appropriate management, according to their medical practice and available resources. In terms of organization and communication, the analysis highlighted shortcomings in the chains of information transmission. Feedback showed the importance of a fluid exchange of information and skills between the different levels of the system, to guarantee rapid and appropriate decision-making. The surveys carried out by the various inspectors gave rise to a series of recommendations, such as the revision of epidemic crisis management procedures, the establishment of a health surveillance system, the provision of additional equipment and resources to carry out screening, clearer identification of contacts and managers in this type of situation, systematic consultation of experts, and improvements in procedures for exchanging information.

6. Conclusion

Military epidemiological management has a complex and multilevel sociotechnical structure. In this kind of system, the occurrence of an incident is dependent on a variety of factors, distributed across the

| Table 3 | Influencing factors and key decisions in descending order of importance. |
|---------|--------------------------------------------------------------------------|
| Factor  | Explanation                                                              |
| 1       | Following the transition to Stage 2 of the epidemic, a series of recommendations is drawn up, providing case definitions for COVID-19 and setting out the diagnostic and epidemiological reporting criteria for the civilian population. |
| 2       | The SSA relies exclusively on these recommendations for the implementation of military epidemiological surveillance strategies. |
| 3       | In the absence of molecular biological testing equipment on board the aircraft carrier, the medical service relies exclusively on the criteria for case definition communicated to it to diagnose possible cases of COVID-19. It fails to detect the presence of cases on board. |
| 4       | The commander decides to continue the aircraft carrier’s medical mission and to maintain the stopover in Brest. |
| 5       | The carrier’s medical service is not aware of new clinical criteria identified by the Directorate of Health and SSA. They attribute the symptoms presented by some sailors to other causes. |
| 6       | Faced with low crew morale and led to believe that the disease is not present on board, the commander decides to relax health and safety measures and allows a concert to take place on board the aircraft carrier. |
| 7       | The carrier commander waits 2 days before informing the authorities of the presence of the disease on board. |
structure. Analysis of the outbreak that occurred on board the aircraft carrier showed the involvement of Levels 2, 4 and 5 in the chain of events leading to the outbreak. This led us to identify a series of factors that influenced the decision taken by the ship’s commander on 30 March. This relaxation of distancing measures, identified as a key tipping point, is clearly linked to the medical team’s failure to detect the virus. The latter seems to have relied solely on the biological criteria that had been communicated to it, without applying any additional strategies that would have allowed it to eliminate all doubt. It turned out that these criteria, defined to guide epidemiological surveillance, were not enough to diagnose the disease. Exchanges with expert bodies would have allowed the team to perform more accurate health assessments. The second key factor highlighted by our analysis also concerns the inadequate transmission of information. Analysis showed that the commander’s decision to manage the internal crisis caused a delay in the intervention of the health authorities. Thus, better communication between the different levels would have made it possible to detect and manage the epidemic more quickly.

Our analysis therefore highlights the importance of good communication between the different levels of the epidemiological management system, for an effective resolution of the situation. As it is, the structural complexity of the system proved to be a source of complication that impeded coordination and cooperation, which are essential in a crisis context. Research in this field has shown that some actors are able “to innovate or to tinker with means of communication or modes of organization for specific circumstances” (Bergeron et al., 2020, p. 102). We believe that this ability is essential for the system to function properly in crisis situations. The findings of social science research show that, in such situations, the procedures and tools available to actors are less important than their ability to work together (Bergeron et al., 2020).

The main objective in improving risk management should be to ensure better interaction between the different levels of the system in terms of decision-making and planning strategies (Rasmussen and Svedung, 2000). The uncontrolled and random factors inherent to crisis situations tend to accentuate the mismatch between the planned measures and the reality on the ground, consequently increasing the risk of incidents. In this type of situation, the actors must rely on their knowledge, while being sufficiently imaginative to create new solutions that will overcome the limitations of their procedures and allow the situation to be managed appropriately (Pellegrin et al., 2021).

The AcciMap method allowed us to perform a causal analysis that went beyond the identification of shortcomings or human errors. As a result, we were able to study the factors that contributed to this incident at all levels of the epidemiological management system and understand how they combined to generate this event. More specifically, the systemic vision afforded by this approach allowed us to go beyond the most direct causes and detect the higher-level factors that influenced the course of events, or which failed to prevent the outbreak taking place. This type of analysis can be applied to a variety of situations. It is particularly useful for revealing the weaknesses of a given system and for drawing lessons and recommendations for improving safety and preventing similar events in the future. Nevertheless, feedback mechanisms should not be limited to pointing out errors or malfunctions that need to be corrected, but should also focus on new solutions for addressing the difficulties that are encountered. Future studies should examine the reorganization strategies and new management methods that were implemented by CESPA’s epidemiological surveillance team during the first phase of the COVID-19 epidemic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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