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An innovative approach for the biological risk management on-board ships during COVID-19 crisis

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ABSTRACT

The novel coronavirus (COVID-19), due to the limited supply of vaccines, put a strain on worldwide economy, also on the maritime sector. As a result, the adoption of non-pharmaceutical interventions to limit the biological agent's spread became fundamental. Such preventing actions can be performed in accordance with various International and National Regulations even though not specifically issued for the maritime sector. In this context, the authors introduce a new methodology for biological risk management on-board ships using a qualitative risk matrix. Moreover, with respect to the traditional approach, an importance weight scale was added, in order to classify the different on-board activities. To perform a comparative analysis between the new and the traditional approach, a case study based on a cargo ship was carried out.

1. Introduction

On the 31st December 2019, the Chinese Health Authorities detected a cluster of pneumonia cases of unknown cause in Wuhan (Hubei region) (Huang et al., 2020). In early January 2020, the Chinese Centre for Disease Control and Prevention identified a novel coronavirus, later named SARS-CoV-2 by the World Health Organization (WHO): the respiratory infection caused by this virus is now called as COVID-19. Due to the spread and the seriousness of symptoms, the WHO declared the COVID-19 outbreak a global pandemic on the 11th March 2020 (World Health Organization, 2020).

With a limited supply of vaccines to prevent the disease, most countries implemented various forms of non-pharmaceutical interventions, including lockdown and social distancing. International, regional and local travel restrictions immediately affected national economies, including tourism systems (Gössling et al., 2020).

Analyzing the COVID-19 effects on economy without considering maritime transport is reductive. Indeed, with over 80% of global trade by volume and more than 70% of its value being carried on board ships and handled by seaports worldwide, maritime transport for trade and development is of paramount importance (UNCTAD, 2020) and represents a key indicator of the global economic condition. As reported in Millefiori et al. (2020), Michail and Melas (2020), Menhat et al. (2021) and Yazır et al. (2020), shipping mobility has been negatively affected, in different manners for each market and depending on the type and size of vessels. Table 1 shows the difference of numbers of stopovers in European Union (EU) ports in the second half of 2019 and 2020 for different types of ships in percentage. In particular, the biggest difference has been identified for cruise ships, passenger ships, chemical tankers, and vehicle carriers. Moreover, for cruise and passenger ships, the number of on-board passengers has significantly decreased (Brewster et al., 2020). As a result, International Agencies are called to give immediate and efficient responses to manage this issue (Doumbia-Henry, 2020; Stannard, 2020; van Tatenhove, 2021).

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Table 1
Stopovers in EU ports per week for different types of ships.

Stopovers in EU ports 2020 vs 2019														
Ship type	Week 32	33	34	35	36	37	38	39	40	41	42	43	44	32-44
Bulk carriers	-5%	8%	-5%	-2%	-6%	-7%	-3%	2%	9%	-5%	12%	1%	-5%	-3%
Chemical tankers	-12%	-31%	16%	-33%	-23%	-10%	-10%	-28%	-23%	-22%	-37%	-35%	-29%	-21%
Container ships	-4%	-5%	-4%	-4%	-2%	-2%	-3%	-9%	0%	-4%	-3%	-5%	-8%	-4%
Cruise ships	-90%	-88%	-88%	-89%	-87%	-86%	-86%	-85%	-82%	-85%	-86%	-85%	-85%	-86%
General cargo ships	-4%	-5%	-5%	-2%	-5%	1%	-4%	-5%	-2%	-4%	0%	-1%	-3%	-3%
Liquefied gas tankers	-6%	-16%	-1%	-13%	2%	-9%	-15%	-7%	1%	-12%	-11%	0%	-1%	-7%
Oil tankers	3%	-4%	-4%	3%	0%	1%	-2%	-8%	-3%	-2%	-8%	-8%	-3%	-3%
Passenger ships	-25%	-24%	-22%	-24%	-21%	-26%	-31%	-42%	-20%	-16%	-30%	-8%	-9%	-24%
RoRo-Pax ships	2%	7%	5%	3%	7%	7%	2%	3%	4%	4%	2%	5%	3%	4%
RoRo-cargo ships	-8%	6%	-3%	0%	-6%	1%	1%	-3%	0%	-1%	-4%	-3%	0%	-2%
Vehicle carriers	-17%	-25%	-21%	-20%	-9%	-23%	-13%	-26%	-12%	-16%	-19%	-10%	-15%	-17%

Table 1 from EMSA, Covid-19 – Impact on Shipping, European Maritime Safety Agency, 6th November 2020

The pandemic situation, along with the lack of passengers and enclosed working environments, has caused instances of psychological imbalance among seafarers (Mittal et al., 2020). In fact, ships can appear as isolated units, but are still vulnerable to biological agents: hence, adopting measures for isolation and containment of COVID-19 is crucial since the first appearance of a symptomatic case (Gostic et al., 2020; Sossai et al., 2020). Indeed, just one infected person could represent an actual risk of transmission for both passengers and crew on-board vessels. In this regard, evaluating the COVID-19 risk associated with the presence of Heating, Ventilation, and Air Conditioning (HVAC) systems is fundamental. In particular, according to the research presented in Chirico et al. (2020), HVAC systems not specifically designed to face coronavirus were suspected of facilitating the spread in hospital and community settings during previous epidemics. Nevertheless, the conclusion that HVAC systems favor the transmission of the COVID-19 infection in offices and indoor community environments (e.g., on-board ships) has not been verified yet. Anyway, precautionary principles should be applied due to the uncertainties of the situation, in order to avoid uncontrolled transmissions of the disease and to guide a safe resumption of operations (European Centre for Disease Prevention and control, 2020; Healthy Sail Panel, 2020). The case of the Diamond Princess cruise ship has been particularly significant, since it represented the first largest coronavirus outbreak outside of mainland China in Rocklöv et al. (2020). After the discovery of the first symptomatic case, the ship was quarantined for over a month in Yokohama harbor: more than 700 persons were infected, out of 3700 persons on board. For its importance in numerical terms numerous studies were performed (Mizumoto et al., 2020; Russell et al., 2020).

All the previous observations led the authors to investigate possible solutions to prevent and minimize the transmission risks of biological agents on-board ships and to support shipowners during the development of the “Risk Assessment Document” (Wang et al., 2020; Wilson et al., 2021).

The present research started from the analysis of the various documents regarding prevention and containment of the biological risk already issued by government agencies, authorities and associations. Furthermore, also the different methodologies implemented for the risk assessment were studied and compared, in order to develop innovative and peculiar methods to deal with the current emergency on-board ships (currently, no specific standards and regulations has been set up for maritime sector). Later, the authors performed a preliminary analysis of the biological risk on-board ships by means of a three-dimensional risk matrix (3D Matrix), which allowed also to identify the riskier activities. Consequently, mitigation and containment measures were defined for each on-board activity. The residual risk was eventually evaluated through both a traditional methodology (adjusted to the maritime sector) and a novel methodology (specifically developed by the authors), and hereby presented. The authors selected a cargo ship as case study due to the availability of the data necessary to perform the proposed analysis. Indeed, even though cruise and passenger ships represent a more interesting case, it must be considered that they have suffered an almost total shipping interdiction since March 2020, while cargo ships suffered a less severe shipping interdiction due to obvious commercial purposes; therefore, the data necessary to apply the proposed methodologies for both cruise and passenger ships were not available.

2. Materials and methods

2.1. Materials

On-board ships, the shipowner is responsible for assessing potential risks and ensuring safety to workers: additionally, he is responsible also for the implementation of the “Risk Assessment Document” (International Maritime Organization, 2005). As regards the biological risk analysis, this has not been declared mandatory yet, despite its importance. Therefore, such an analysis was performed in accordance with various International and National Regulations not specifically issued for the maritime sector.

In addition to this, due to the fact that every State is in charge to regulate navigation authorization and to promulgate safety certification, National Regulations should be analyzed nation by nation. However, in this paper the authors focused on the Italian situation as a representative of all the others, so a novel certification developed to manage biological risks on-board ships and issued by the Classification Society Registro Italiano Navale (RINA) was considered.

First of all, it is important to note that the Italian Legislative Decree 271/99 (Parlamento Italiano, 1999) imposes several safeguard measures for seafarers working on merchant ships to both prevent injuries and guarantee workplace hygiene. The shipowner is responsible for both providing the necessary equipment and the application of all these actions. With respect to biological risks, the Italian Legislative Decree 81/08 Annex XLVI (Parlamento Italiano, 2008) provides a classification for the biological agents able to cause infectious diseases in persons. The classification methodology is based on the effects of the various agents on healthy workers; indeed, it does not take into account the situations in which a person's health can be compromised by other causes. Biological agents can belong to one of the following categories:

- Group 1: agents with a low probability of causing diseases in persons;
- Group 2: agents that may cause diseases in persons and represent a risk for workers. Their spread is unlikely to happen and usually effective preventive or therapeutic measures are available;
- Group 3: agents that may cause severe diseases in persons and represent a serious risk for workers. Their spread can happen, but usually effective preventive or therapeutic measures are available;
- Group 4: agents that may cause severe diseases in persons and represent a serious risk for workers. Their spread is likely to happen and usually effective preventive or therapeutic measures are not available.

The SARS-CoV-2 virus, which belongs to the Coronaviridae family, was classified as Group 3 due to its characteristics in accordance with the Directive 2020/739 (Official Journal of the European Union, 2020).

It is important to note that the Legislative Decree 271/99 refers to different International Regulations such as Council Directive 92/91/EEC (European Council, 1992a) and Council Directive 92/104/EEC (European Council, 1992b), other than the International Convention for the Safety of Life at Sea (SOLAS) (International Maritime Organization, 1974); therefore, it can be asserted that other States adopted the same safeguard measures for seafarers.

In order to perform the biological risk assessment, authors identified three Regulations providing useful guidelines. The first is the UNI ISO 31000:2018 (UNI, 2018a), in which the following phases for the risk evaluation are presented:

- Risk identification and description;
- Risk analysis;
- Risk weighting (in terms of relative importance).

Related to the latter Regulation, the UNI CEI EN IEC 31010:2019 (UNI, 2019) identifies the following phases for the implementation of the risk assessment:

- Risk assessment planning;
- Information management and model development;
- Application of risk assessment techniques;
- Supporting the decisions in terms of actions and risk importance by applying the results obtained through the previous phases;
- Registering and providing documentary evidences about the process and the risk assessment outcomes.

Furthermore, Regulation ISO 45001:2018 has been considered, specifying requirements for an Occupational Health and Safety (OH&S) management system and giving guidance for its use (UNI, 2018b).

Eventually, in addition to the ISO Rules explained above, the "Biosafety Trust Certification" issued by the RINA can be taken into account (RINA, 2020). Indeed, the main aim of this certification is to manage, prevent, and mitigate the diffusion of infections on-board ships. To obtain the Biosafety Trust Certification, shipping companies have to both perform a thorough risk assessment and implement proper mitigation measures. In particular, the following factors must be considered:

- Organization processes;
- Types of infections;
- Transmission modalities;
- High-risk processes;
- Probabilistic assessment of recurrence;
- Potential seriousness.

The Biosafety Trust Certification can be obtained when a target value, called "BIOSAFE Index", is reached; this index is based on the following parameters:

- Spaces layout on-board;
- Materials, systems and components of ship plants;
- Procedures;
- Training and experience of the crew.

On the basis of the Regulations analyzed and described above, a new methodology for the evaluation of the risks related to the COVID-19 pandemic outbreak has been implemented. In particular, a schematic of the new methodology is reported in Fig. 1: after a first phase of context overview, where all the possible on-board ship risks (mainly biological, physical, psychological and managerial) are identified and analyzed, a qualitative risk matrix is evaluated to define the possible reduction measures to adopt and the acceptable level to achieve (UNI, 2018b). Specifically, according to ISO 45001:2018, the acceptable risk level to be reached is the ALARP level (As Low as Reasonable Practicable).

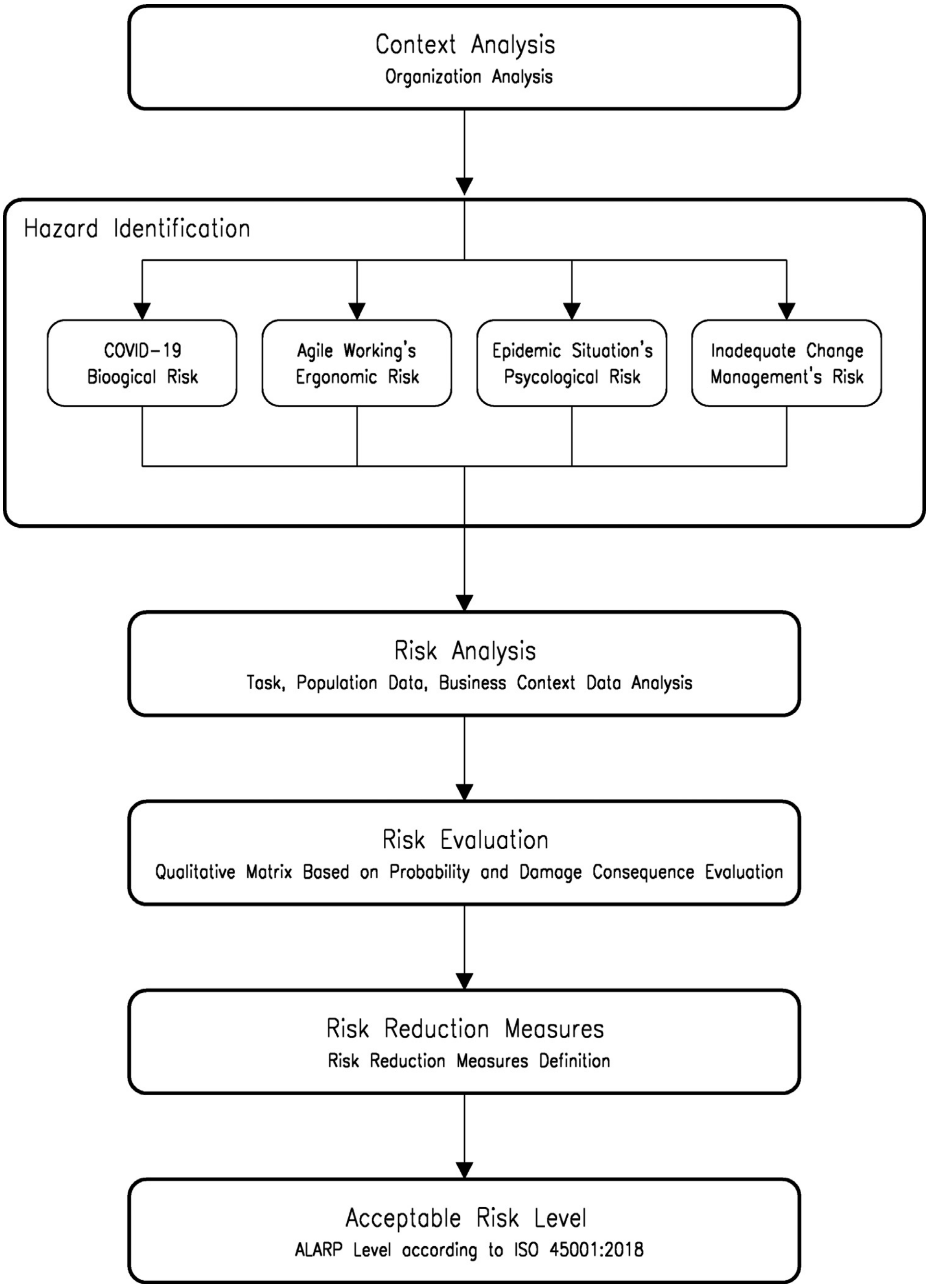

Fig. 1. Method for evaluating COVID-19's risks - Block diagram.

2.2. Methods

The contents described in the previous section represent the basis for identifying and defining useful and necessary actions to prevent the spread of biological agents on-board ships.

2.2.1. Initial risk and 3D matrix

To provide technical support for the determination of intervention priorities, all the on-board activities that may contribute for risk characterization must be analyzed. To determine which ones could be the most dangerous in terms of biological agents spread,

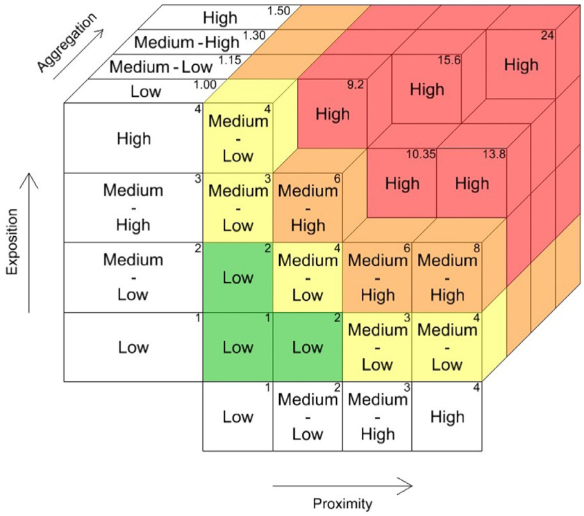

Fig.2. 3D Matrix.

three different factors were numerically evaluated. These factors, with the relevant rating system used for the analysis, are hereafter listed:

- *Exposition*: defined as the probability to be exposed to sources of contamination during specific employment activities, it can take values between 1 (low exposition, the sources of contamination seem limited) and 4 (high exposition, the sources of contamination seem several);
- *Proximity*: defined as a group of inherent characteristics of activities that cannot permit a sufficient social distance, it can take values between 1 (low proximity, the work is carried out alone for most of the time/the work is carried out with others but, for most of the time, not in proximity) and 4 (high proximity, the work is carried out with others for most of the time in proximity);
- *Aggregation*: defined as the type of work which includes the contact with third parties (other than workers), it can take these values:

■ 1.00: low aggregation, zero/limited presence of third parties;
■ 1.15 (+15%): medium-low aggregation, inherent presence of third parties but controllable with organization;
■ 1.30 (+30%): medium-high aggregation, inherent presence of third parties but controllable with procedures;
■ 1.50 (+50%): high aggregation, inherent presence of third parties limitedly controllable with procedures.

Once the values of Exposition (Ex), Proximity (Pr) and Aggregation (Ag) have been allocated to every on-board activities, the initial risk R_0 can be determined as follows:

$$R_0 = Ex \cdot Pr \cdot Ag \quad (1)$$

To graphically identify the biological initial risk contagion, a three-dimensional risk matrix (3D Matrix, Fig. 2) was used, developed from the one employed in the industrial sector (as defined in Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, 2020) and adapted for on-board activities. The 3D Matrix defines four different range of values, in which the biological initial risk level is:

- Low: $R_0 \le 2$;
- Medium-low: $2 < R_0 \le 4$;
- Medium-high: $4 < R_0 \le 8$;
- High: $R_0 > 8$.

2.2.2. Residual risk

The initial risk R_0 does not take into account all the prevention and protection measurements adopted to reduce the spread of biological agents on-board ships. To consider these reduction actions, a new evaluation risk parameter R should be introduced.

The biological residual risk R is defined as the product between the probability of dangerous event occurrence P and the damage consequence D in case the event happens:

$$R = P \cdot D \quad (2)$$

To distinguish the biological risk level given by R from that one given by R_0, four other different ranges of values are defined, in which the biological risk level is:

- Low: $R \le 2$;

- Medium-low: $2 < R \leq 8$;
- Medium-high: $8 < R \leq 10$;
- High: $10 < R \leq 16$.

The damage D can be determined according to the higher value of the biological agents group as reported in section "Materials". It can assume the following values:

- 1: mild damage;
- 2: modest damage;
- 3: serious damage;
- 4: extremely serious damage.

The probability P can be assumed through an index ranging from 1 (low probability of infection) to 4 (high probability of infection), and it is determined by the following formula:

$$P = \frac{C \cdot \sum_{i=1}^{N} \left(F_i + 1\right)}{N + 1} \quad (3)$$

where F_i factors represent the ways of organising work (as defined in (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, 2017)) and C represents the parameter of alleged contamination from biological agent (it can assume values from 1, alleged contamination very low, to 4, alleged contamination high. In case of indoor-air/bio-aerosol/confined spaces $C = 4$).

2.2.3. F_i factors – traditional vs new methodological approach

The risk reduction actions are incorporated inside the F_i factors, as follows:

- F_1: Affluence. Number of crew members that should be employed for the activity;
- F_2: Frequency. It takes into account how many people are necessary for the on-board activity in question, if it is necessary to work in proximity to each other and for how long;
- F_3: Structural features. Set of useful characteristics able to interrupt effectively the biological agents ways of transmission;
- F_4: Procedures and good practices. Set of procedures and practices aimed at managing the biological risk, formalized for all the crew members;
- F_5: Personal Protective Equipment (PPE). Types of PPE used to carry out the on-board activity in question (Cook, 2020). Furthermore, it takes into account how long the PPE is really used;
- F_6: Training. It takes into account the number of crew members prepared to face biological emergency. It includes all the following information: knowledge of possible pathogens, ways of transmission and related exposure risk, procedures and systems for prevention and protection, use of PPE and Collective Protection Equipment (CPE), biological waste management and procedures to apply in case of emergency.

To estimate the values of F_i factors, a two-group subdivision was carried out:

1 F_i "with options": in this group F_i can assume the value 0, 0.5 or 1, depending on the boundary conditions regarding the possible ways to perform a specific on-board activity (number of crew members involved, shared spaces and times on the activity, level of preparation for facing the biological risk). For example, the factor F_1 (affluence) is equal to 0 if the on-board activity under analysis is performed by only one crew member (the biological risk is low), it is equal to 0.5 if the activity is performed by two or three crew members (the biological risk is medium) and it its equal to 1 if the activity is performed by more than three crew members (the biological risk is high). This concept can be expressed through the following formula:

$$F_i = \{\begin{matrix} 0 & if\ option\ 1\ is\ true \\ 0.5 & if\ option\ 2\ is\ true \\ 1 & if\ option\ 3\ is\ true \end{matrix} \quad (4)$$

F_1, F_2 and F_6 belong to this group (Table 2).

1 F_i "with a list of measures able to reduce biological risk": in this group F_i can assume the value 0, 0.5 or 1, depending on the ratio in percentage ($\%r$) between the measures "really applied" and the whole measures considered as "necessary to be applied" (Table 3):

$$\%r = 100\frac{EA}{NA} \quad (5)$$

Where NA (Necessary to be applied) represents the number of measures necessary to reduce biological risk for a specific on-board activity (such as, for example, wearing masks or being compliance with anti-COVID-19 behavioural rules) and EA (Effectively Applied) represents the number of the same measures considered in NA that were effectively applied. The complete list of the measures is presented in Table 4. For example, to reduce biological risk for the activity number 15 (Safety and evacuation drills) and considering the factor F_3 (structural features), three measures out of four are necessary ($NA = 3$) but only one of them is effectively applied ($EA = 1$). So, formula (5) gives that $\%r = 100\frac{EA}{NA} = 100\frac{1}{3} = 33\%$. As a consequence, F_3 assumes a value equal to 1 (high risk) on the basis of its value scale. F_3, F_4 and F_5 belong to this group (Table 3).

Table 2
F_i first group – factor domain and values assumed.

Factor	Factor domain	Values assumed F_i	Risk classification
Affluence F_1	1 crew member	0	Low
	2-3 crew members	0.5	Medium
	> 3 crew members	1	High
Frequency F_2	Work alone for most of the time/work with others but not in close proximity	0	Low
	Work with others in shared spaces and on tasks that require close proximity with others but for a non-predominant part of the time	0.5	Medium
	Work done in close proximity to others for most of the time	1	High
Training F_6	All the crew members exposed to the biological risk received specific training and information	0	Low
	Only part of the crew members received specific training and information (more than 50%)	0.5	Medium
	Out of the crew members exposed to biological risk less than 50% received specific training and information	1	High

Table 3
F_i second group – values assumed.

Factor	$\%r$	Values assumed F_i	Risk classification
Structural features F_3	$r = 100\%$	0	Adequate
	$66\% \le r < 100\%$	0.5	Partially adequate
	$r < 66\%$	1	Not adequate
Procedures and good practice F_4	$r = 100\%$	0	Adequate
	$75\% \le r < 100\%$	0.5	Partially adequate
	$r < 75\%$	1	Not adequate
Personal Protective Equipment (PPE) F_5	$r = 100\%$	0	Adequate
	$50\% \le r < 100\%$	0.5	Partially adequate
	$r < 50\%$	1	Not adequate

Table 4
F_i second group – list of measures.

Factor	List of measures
Structural feature F_3	Presence of washable floors and work surfaces
	Presence of sinks and/or disinfectant gel dispensers
	Adequate exchange of natural or forced air
	Presence of spacer devices (e.g., plexiglas barrier)
Procedures and good practice F_4	Hand hygiene
	Use of PPE
	Correct replacement of PPE
	Interpersonal distance of at least 1 m
	Compliance with anti-COVID-19 behavioural rules
	Operational/management procedures for the correct management of COVID-19 biological risk
	Periodic sanitation of surfaces and objects
	Correct storage and disposal of PPE
	Adequate maintenance and cleaning of ventilation, air conditioning and heating systems
Personal Protective Equipment (PPE) F_5	Masks
	Gloves
	Disposable gowns
	Shoe covers
	Glasses

The method for the calculation of the above-described ratio $\%r$ is based on a traditional approach that does not take into account the importance of the adoption of a specific measure (i.e., wearing masks, gloves, shoe covers and glasses). Therefore, in order to add this consideration within the risk analysis, a new approach based on the implementation of a weight scale, which identifies how much the adoption of a certain measure can reduce the biological risk, has been set up. The formula for the modified (weighted) ratio in percentage $\%r$ is given as follows:

$$\%r = 100\frac{\sum_{j=1}^{N} EA_j Weight_j}{\sum_{j=1}^{N} NA_j Weight_j} \tag{6}$$

Where NA_j (Necessary Applied) represents the *j*-th measure necessary to reduce biological risk for a specific on-board activity (such as, for example, wearing masks or being compliance with anti-COVID-19 behavioral rules), EA_j (Effectively Applied) represents the *j*-th measure effectively applied and $Weight_j$ represents the *j*-th weight of the on-analysis measure, which may range from 1 (measures

Table 5
Main on-board activities for a cargo ship and crew members involved.

Main on-board activities for a cargo ship		Crew members involved in the activity
1	Navigation (Navigation Bridge)	6
2	Propulsion (Engine Control Room)	4
3	Auxiliary machines control	2
4	Machinery Maintenance - Engine Room	8
5	Machinery Maintenance - Ship Deck (minor operations)	7
6	Services in the Mechanical and Electrical Workshop	4
7	Manoeuvres of Lifting Equipment and Means of Opening/Access	3
8	Inspections of Cargo Compartments and Ballast Compartments	2
9	Steel Carpentry - Piping - Welding and Flame Cuts	3
10	Deck Manoeuvres (Mooring/Unmooring/Anchoring)	5
11	Loading or Discharging Operation - Cargo Control Room	3
12	Load control during transportation	1
13	Cleaning Accommodation	1
14	Kitchen work	3
15	Safety and evacuation drills	20
16	Recreational	10
17	Hygiene and Personal Care (i.e., Laundry)	2

not very important) to 5 (measures very important). Thus, F_i can assume a value of 0, 0.5 or 1, depending on the weighted ratio in percentage ($\%r$) between the measures "really applied" and the whole measures considered as "necessary to be applied".

3. Calculation

In order to ensure the uninterrupted service of cargo ships (necessary for obvious commercial purposes) and without available data to apply the proposed methodologies on a cruise/passenger-ship case study (due to an almost total shipping interdiction since March 2020), the cargo-ship case study was considered as primary in respect to passenger-ship ones and hence was deeply investigated by the authors (in accordance with the request of Flag authority) to determine the on-board activities having the most serious biological risk in terms of contamination agent spreading. The main on-board activities (as reported in the legislative degree 271/99 and classified of paramount importance during on-site interviews with crew members) and the relevant number of crew members employed in such activities (as derived from a significant example of a crude oil tanker) were collected in Table 5.

The initial risk R_0 was calculated for each activity listed in Table 5. By considering the definitions previously introduced in section "Methods", values for Exposition, Proximity and Aggregation were assigned. Then, the so calculated R_0 values were crosschecked with the ones reported in the 3D Matrix in order to assess which on-board activities present the higher level of risk (Table 6).

Starting from initial risk R_0 calculation, the residual risk R is evaluated for every on-board activity that presents a R_0 value not equal to "Low". For each activity, a summative table for F_i factors determination was created. Specifically, as an example, in Tables 7 and 8 is reported the F_i evaluation (using both the traditional and the new methodology) with reference to the activity "Safety and evacuation drills" on a cargo ship.

Considering a parameter of alleged contamination from biological agent C equal to 4 (value applied to indoor-air/bio-aerosol/confined spaces), the probability of dangerous event occurrence P was calculated for each on-board activity.

From the product between P and the damage consequence D (considered equal to 3 for all the tasks, serious damage), the residual risk R for all on-board activities can be evaluated (Tables 9 and 10, where LR indicates an activity with a Low Risk level excluded from calculation).

4. Results and discussion

From the analysis of the results collected in Table 11 it appears that the activities having the lowest value for R_0 are "Auxiliary machines control" ($R_0 = 2$) and "Load control during transportation" ($R_0 = 1$). Therefore, these activities were excluded from the R calculation (indeed, the adoption of risk reduction actions can only decrease the biological risk on-board ship).

The analysis of the residual risk R values calculated through both the traditional and the new approach led to the following considerations:

- The activities related to "Machinery Maintenance - Ship Deck (minor operations)", "Inspections of Cargo Compartments and Ballast Compartments", "Deck Manoeuvres (Mooring/Unmooring/Anchoring)", "Cleaning Accommodation", "Recreational" and "Hygiene and Personal Care (i.e., Laundry)" present the same values, regardless the approach;
- All the others activities present a higher value in case of the new approach application. However all the activities keep the same risk level (medium-low) except the activity "Safety and evacuation drills", which levels up from medium-low (traditional approach, $R = 7.71$) to medium-high risk (new approach, $R = 8.58$).

A final consideration regarding interdependences among the various on-board activities in terms of virus spread must be drawn. Indeed, it is clear that the sequence in which each activity is performed is a fundamental factor. In other words, the risk of contracting

Table 6
R_0 evaluation and level of risk for every on-board activities.

Main on-board activities for a cargo ship		Exposition (Ex)	Proximity (Pr)	Aggregation (Ag)	R_0	Level of risk
1	Navigation (Navigation Bridge)	2	2	1.15	4.6	Medium-high
2	Propulsion (Engine Control Room)	2	2	1.15	4.6	Medium-high
3	Auxiliary machines control	1	2	1	2	Low
4	Machinery Maintenance - Engine Room	3	3	1.5	13.5	High
5	Machinery Maintenance - Ship Deck (minor operations)	3	3	1.5	13.5	High
6	Services in the Mechanical and Electrical Workshop	3	3	1.6	13.5	High
7	Manoeuvres of Lifting Equipment and Means of Opening/Access	2	3	1.3	7.8	Medium-high
8	Inspections of Cargo Compartments and Ballast Compartments	2	4	1.3	10.4	High
9	Steel Carpentry - Piping - Welding and Flame Cuts	2	4	1.3	10.4	High
10	Deck Manoeuvres (Mooring/Unmooring/Anchoring)	2	3	1.15	6.9	Medium-high
11	Loading or Discharging Operation - Cargo Control Room	1	2	1.15	2.3	Medium-low
12	Load control during transportation	1	1	1	1	Low
13	Cleaning Accommodation	3	1	1	3	Medium-low
14	Kitchen work	1	2	1.15	2.3	Medium-low
15	Safety and evacuation drills	3	3	1.15	10.35	High
16	Recreational	3	4	1	12	High
17	Hygiene and Personal Care (i.e., Laundry)	3	1	1	3	Medium-low

Table 7
F_i Evaluation – example for the activity “Safety and evacuation drills” (traditional approach).

Factor	Factor domain	Option choice	F_1		
Affluence F_1	1 crew member		0		
	2-3 crew members		0.5		
	> 3 crew members	X	1		
Factor	Factor domain	Option choice	F_2		
Frequency F_2	Work alone for most of the time /work with others but not in close proximity		0		
	Work with others in shared spaces and on tasks that require close proximity with others but for a non-predominant part of the time		0.5		
	Work done in close proximity to others for most of the time	X	1		
Factor	List of measures	Necessary	Applied	%r	F_3
Structural features F_3	Presence of washable floors and work surfaces	YES	NO	33	1
	Presence of sinks and/or disinfectant gel dispensers	YES	NO		
	Adequate exchange of natural or forced air	YES	YES		
	Presence of spacer devices (e.g. plexiglas barrier)	NO	-		
Factor	List of measures	Necessary	Applied	%r	F_4
Procedures and good practice F_4	Hand hygiene	YES	YES	78	0.5
	Use of PPE	YES	YES		
	Correct replacement of PPE	YES	YES		
	Interpersonal distance of at least 1 m	YES	NO		
	Compliance with anti COVID-19 behavioural rules	YES	YES		
	Operational/management procedures for the correct management of COVID-19 biological risk	YES	YES		
	Periodic sanitation of surfaces and objects	YES	YES		
	Correct storage and disposal of PPE	YES	YES		
	Adequate maintenance and cleaning of ventilation, air conditioning and heating systems	YES	NO		
Factor	List of measures	Necessary	Applied	%r	F_5
Personal Protective Equipment (PPE)	Masks	YES	YES	100	0
	Gloves	YES	YES		
	Disposable gowns	NO	-		
	Shoe covers	NO	-		
	Glasses	YES	YES		
Factor	Factor domain	Option choice	F_6		
Training F_6	All the crew members exposed to the biological risk received specific training and information	X	0		
	Only part of the crew members received specific training and information (more than 50%)		0.5		
	Out of the crew members exposed to biological risk less than 50% received specific training and information		1		

Table 8
F_i Evaluation – example for the activity “Safety and evacuation drills” (new approach).

Factor	Factor domain	Option choice	F_1			
Affluence	1 crew member		0			
F_1	2-3 crew members		0.5			
	> 3 crew members	X	1			
Factor	Factor domain	Option choice	F_2			
Frequency	Work alone for most of the time /work with others but not in close proximity		0			
F_2	Work with others in shared spaces and on tasks that require close proximity with others but for a non-predominant part of the time		0.5			
	Work done in close proximity to others for most of the time	X	1			
Factor	List of measures	Necessary	Applied	Weight	%r	F_3
Structural	Presence of washable floors and work surfaces	YES	NO	4	36	1
fea-	Presence of sinks and/or disinfectant gel dispensers	YES	NO	5		
tures	Adequate exchange of natural or forced air	YES	YES	5		
F_3	Presence of spacer devices (e.g. plexiglas barrier)	NO	-	5		
Factor	List of measures	Necessary	Applied	Weight	%r	F_4
Procedures	Hand hygiene	YES	YES	5	74	1
and	Use of PPE	YES	YES	5		
good	Correct replacement of PPE	YES	YES	3		
prac-	Interpersonal distance of at least 1 m	YES	NO	5		
tice	Compliance with anti COVID-19 behavioral rules	YES	YES	4		
F_4	Operational/management procedures for the correct management of COVID-19 biological risk	YES	YES	3		
	Periodic sanitation of surfaces and objects	YES	YES	5		
	Correct storage and disposal of PPE	YES	YES	4		
	Adequate maintenance and cleaning of ventilation, air conditioning and heating systems	YES	NO	5		
Factor	List of measures	Necessary	Applied	Weight	%r	F_5
Personal	Masks	YES	YES	5	100	0
Pro-	Gloves	YES	YES	4		
tec-	Disposable gowns	NO	-	4		
tive	Shoe covers	NO	-	3		
Equip-	Glasses	YES	YES	3		
ment (PPE) F_5 / Factor	Factor domain	Option choice	F_6			
Training	All the crew members exposed to the biological risk received specific training and information	X	0			
F_6	Only part of the crew members received specific training and information (more than 50%)		0.5			
	Out of the crew members exposed to biological risk less than 50% received specific training and information		1			

Table 9
Residual risk calculation for every on-board activity (traditional approach).

Main on-board activities for a cargo ship		F_1	F_2	F_3	F_4	F_5	F_6	P	D	R	Level of risk
1	Navigation (Navigation Bridge)	1	0.5	0.5	0.5	0	0	2	3	6	Medium-low
2	Propulsion (Engine Control Room)	1	0.5	0.5	0.5	0	0	2	3	6	Medium-low
3	Auxiliary machines control	LR	LR	LR	LR	LR	LR	LR	LR	LR	Low
4	Machinery Maintenance - Engine Room	1	0.5	0	0.5	0	0	1.71	3	5.13	Medium-low
5	Machinery Maintenance - Ship Deck (minor operations)	1	0.5	1	0.5	0	0	2.29	3	6.87	Medium-low
6	Services in the Mechanical and Electrical Workshop	1	0.5	0	0.5	0	0	1.71	3	5.13	Medium-low
7	Manoeuvres of Lifting Equipment and Means of Opening/Access	0.5	0.5	1	0.5	0	0	2	3	6	Medium-low
8	Inspections of Cargo Compartments and Ballast Compartments	0.5	1	1	1	0	0	2.57	3	7.71	Medium-low
9	Steel Carpentry - Piping - Welding and Flame Cuts	0.5	1	0	0.5	0	0	1.71	3	5.13	Medium-low
10	Deck Manoeuvres (Mooring/Unmooring/Anchoring)	1	0.5	1	0.5	0	0	2.29	3	6.87	Medium-low
11	Loading or Discharging Operation - Cargo Control Room	0.5	0.5	0.5	0.5	0	0	1.71	3	5.13	Medium-low
12	Load control during transportation	LR	LR	LR	LR	LR	LR	LR	LR	LR	Low
13	Cleaning Accommodation	0	0	0	0.5	0	0	0.86	3	2.58	Medium-low
14	Kitchen work	0.5	0.5	0	0.5	0.5	0	1.71	3	5.13	Medium-low
15	Safety and evacuation drills	1	1	1	0.5	0	0	2.57	3	7.71	Medium-low
16	Recreational	1	1	0.5	1	0	0	2.57	3	7.71	Medium-low
17	Hygiene and Personal Care (i.e., Laundry)	0.5	0	0	0.5	0	0	1.14	3	3.42	Medium-low

Table 10
Residual risk calculation for every on-board activity (new approach).

Main on-board activities for a cargo ship		F_1	F_2	F_3	F_4	F_5	F_6	P	D	R	Level of risk
1	Navigation (Navigation Bridge)	1	0.5	0.5	1	0	0	2.29	3	6.87	Medium-low
2	Propulsion (Engine Control Room)	1	0.5	0.5	1	0	0	2.29	3	6.87	Medium-low
3	Auxiliary machines control	LR	LR	LR	LR	LR	LR	LR	LR	LR	Low
4	Machinery Maintenance - Engine Room	1	0.5	0	1	0	0	2	3	6	Medium-low
5	Machinery Maintenance - Ship Deck (minor operations)	1	0.5	1	0.5	0	0	2.29	3	6.87	Medium-low
6	Services in the Mechanical and Electrical Workshop	1	0.5	0	1	0	0	2	3	6	Medium-low
7	Manoeuvres of Lifting Equipment and Means of Opening/Access	0.5	0.5	1	1	0	0	2.29	3	6.87	Medium-low
8	Inspections of Cargo Compartments and Ballast Compartments	0.5	1	1	1	0	0	2.57	3	7.71	Medium-low
9	Steel Carpentry - Piping - Welding and Flame Cuts	0.5	1	0	1	0	0	2	3	6	Medium-low
10	Deck Manoeuvres (Mooring/Unmooring/Anchoring)	1	0.5	1	0.5	0	0	2.29	3	6.87	Medium-low
11	Loading or Discharging Operation - Cargo Control Room	0.5	0.5	0.5	1	0	0	2	3	6	Medium-low
12	Load control during transportation	LR	LR	LR	LR	LR	LR	LR	LR	LR	Low
13	Cleaning Accommodation	0	0	0	0.5	0	0	0.86	3	2.58	Medium-low
14	Kitchen work	0.5	0.5	0	1	0.5	0	2	3	6	Medium-low
15	Safety and evacuation drills	1	1	1	1	0	0	2.86	3	8.58	Medium-high
16	Recreational	1	1	0.5	1	0	0	2.57	3	7.71	Medium-low
17	Hygiene and Personal Care (i.e., Laundry)	0.5	0	0	0.5	0	0	1.14	3	3.42	Medium-low

Table 11
Results confrontation - cargo ship.

Main on-board activities for a cargo ship		R_0	R - Traditional approach	R - New approach
1	Navigation (Navigation Bridge)	4.6	6	6.87
2	Propulsion (Engine Control Room)	4.6	6	6.87
3	Auxiliary machines control	2	LR	LR
4	Machinery Maintenance - Engine Room	13.5	5.13	6
5	Machinery Maintenance - Ship Deck (minor operations)	13.5	6.87	6.87
6	Services in the Mechanical and Electrical Workshop	13.5	5.13	6
7	Manoeuvres of Lifting Equipment and Means of Opening/Access	7.8	6	6.87
8	Inspections of Cargo Compartments and Ballast Compartments	10.4	7.71	7.71
9	Steel Carpentry - Piping - Welding and Flame Cuts	10.4	5.13	6
10	Deck Manoeuvres (Mooring/Unmooring/Anchoring)	6.9	6.87	6.87
11	Loading or Discharging Operation - Cargo Control Room	2.3	5.13	6
12	Load control during transportation	1	LR	LR
13	Cleaning Accommodation	3	2.58	2.58
14	Kitchen work	2.3	5.13	6
15	Safety and evacuation drills	10.35	7.71	8.58
16	Recreational	12	7.71	7.71
17	Hygiene and Personal Care (i.e., Laundry)	3	3.42	3.42

the virus for a crew member depends on the activities previously carried out by the others. However, in this first analysis crew members are considered in a more generic way, without categorizing them on the basis of their specific role and activities on-board. As a result, it is difficult to properly define the correct sequence of activities which could have an impact on the virus contraction. For sure, future developments of the studies will take this paramount aspect into account by classifying in a more precise way all the crew members in relation with their primary roles on-board.

5. Conclusion

The COVID-19 outbreak has an enormous impact on the economy of every country, and also in the maritime sector. The adoption of mitigation actions (i.e., lockdown, international travel restrictions) is fundamental to limit the pandemic, but, without an analysis carried out to highlight how the biological agents can spread and which activities can be the most dangerous ones, such mitigation actions by themselves are not enough. Therefore, a study to identify a methodology able to classify the biological agents spread on-board ships has been set up with the introduction of two different types of risk parameters: the initial risk R_0 (which classifies the potentially most dangerous activities by a 3D Matrix) and the residual risk R. Moreover, R has been defined through two different approaches: one based on a traditional analysis and the other on an innovative procedure, which considers the importance of the measures adopted introducing adequate weights.

In conclusion, a comparison of R_0 and R, based on the two above-mentioned approaches, was performed, and the most dangerous on-board activities were identified. In particular, the new approach proposed by the authors set higher safety levels than the traditional one.

Future development of this study will consider mitigation actions based on the adoption of new technical solutions for HVAC systems. In particular, the adoption of KOALA^{TM} filters is currently under examination by authors on a naval ship. Moreover, a cruise ship case study, much more complex than the cargo ship presented in this work, will be analyzed.

The approach presented in this work is under consideration for the adoption by the Italian Flag Authority, and also by the RINA (Registro Italiano Navale).

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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