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A decision-making framework to reduce the risk of collisions between ships and whales

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ABSTRACT

Ship strikes are one of the main human-induced threats to whale survival. A variety of measures have been used or proposed to reduce collisions and subsequent mortality of whales. These include operational measures, such as mandatory speed reduction, or technical ones, such as detection tools. There is, however, a lack of a systematic approach to assessing the various measures that can mitigate the risk of ship collisions with whales. In this paper, a holistic approach is proposed to evaluate mitigation measures based on a risk assessment framework that has been adopted by the International Maritime Organization (IMO), namely the Formal Safety Assessment (FSA). Formal Safety Assessment (FSA) is "*a rational and systematic process for assessing the risk related to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO's options for reducing these risks*". The paper conceptualizes the use of a systematic risk assessment methodology, namely the FSA, to assess measures to reduce the risk of collisions between ships and whales.

1. Introduction

Cetaceans face several threats to survival. Most of these threats are human-induced or amplified by human activities: whaling [1–3], entanglement [4], ship collisions [5,6], ocean noise [7], pollution [8], climate change [9]. While difficult to quantify, ship collisions are known to be major threats to whales [5,6]. The severity of the threat arises due to three main factors. First, the overlap between areas with a high density of whales and ships creates areas with high probabilities of encounters [10,11]. Second, collisions that do occur have a high probability of whale mortality. Indeed, at a ship speed of 12 knots, there is a 50% probability of whale mortality following a collision event. This probability reaches respectively 70% and 90% at 14kn and 18kn [12]. Third, the risk of collision also has increased over the years as a result of increased ship traffic [13,14]. Combined, these factors contribute to an ever-growing threat to whale survival. Many authors highlight that the level of threat in certain areas put at risk the populations' survival (e.g., Mediterranean fin whales (*Balaenoptera physalus*) and sperm whales (*Physeter macrocephalus*), New Zealand Bryde's whales (*Balaenoptera edeni*) [15–17]). The most illustrative case remains the North Atlantic right whales (*Eubalaena glacialis*). This population is likely to be extinct within approximately 200 years if the collision issue is left unmanaged [18].

A variety of approaches have been developed to reduce the threat of collisions with ships. These approaches can be classified as either operational or technical measures. Operational measures are related to approaches that involve a change in the way ships navigate. The more widespread operational management tools are: area to be avoided (ATBA), traffic separation schemes (TSS), or speed reduction (SR) [19–23]. Technical measures include onboard and off-board tools to detect whales, among others: visual observation networks (e.g., the Real-Time Plotting of Cetaceans System - REPCET, Whale Alert, Whale Safe), acoustic networks, dedicated observers, thermal night navigator, and predictive modeling [24–28].

The lack of a holistic approach covering the cost-effectiveness, the regulatory regime, and the compliance of existing collision avoidance tools, are likely to have been barriers to the successful implementation of the various measures. Often, cost, compliance, risk reduction, and

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regulatory status are parameters independently studied when considering the whale collision issue (cf. Supplementary Material S1). Indeed, the lack of a holistic view prevents the adoption of mitigation measures and has been used by shipping industries as an excuse not to act [5,29,30]. To be noted that some successful cases dealing with ship-whale collision have integrated a more holistic approach, leading to higher compliance of the shipping industry (e.g., Panama [31]), even engaging them in voluntary actions [17]. The North Atlantic right whales case is a good illustration of the processing of several parameters to achieve a successful interdisciplinary approach [24,32]. Constantine et al. [17], also proved that the implication of the shipping industry stakeholders in the New Zealand Bryde's whale collision issue could lean towards voluntary mitigation actions and engage the shipping industry toward social license [33].

As highlighted in the recommendations of the 2019 Conference on Marine Mammal Protected Areas (ICMMPA), a more holistic approach to reducing the risk of collision between ships and whales, for instance, through risk assessment, is needed. One such way to standardize these assessments is the Formal Safety Assessment (FSA) used by the International Maritime Organization (IMO). The FSA is *"a rational and systematic process for accessing the risk related to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO's options for reducing these risks"* (see FSA Guidelines in Ref. [34]). The use of the FSA for environmental issues is somewhat limited and has mainly focused on oil spills [35,36]. However, the use of the Formal Safety Assessment (FSA) could be a way to standardize and better assess the potential of proposed solutions to reduce whale collisions.

The IMO is a United Nations organization that deals with all aspects of maritime safety and the protection of the marine environment. The IMO's primary objective is to develop and maintain a comprehensive regulatory framework for shipping [37]. The management of safety at sea is based on a set of accepted rules that are, in general, agreed through the IMO. The work of the IMO on the protection of whales has been somewhat limited. So far, the IMO has issued few resolutions and amendments towards the avoidance of whale collision, mainly focused on rerouting [38,39] or areas to be avoided [40]. While governments and organizations, such as the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) and the International Whaling Commission (IWC), have submitted various proposals to the IMO [41,42], it is difficult for the IMO to evaluate the proposed solutions. Indeed, the submitted cases follow an unstandardized format and do not account for the impact of these solutions on maritime traffic. These submissions often provide redundant information, such as just guidance to reduce collisions [43–47]. The IMO hardly ever adopts these incomplete recommendations [41] or only endorses them when the local regulations are pro-active [31].

The objective of this paper is to conceptualize the use of the Formal Safety Assessment to address collisions between ships and whales. There are several challenges to this approach that the paper will outline in the following sections. For each step of the FSA, we discuss how this framework can be used within the scope of assessing the risks to whales.

2. Using Formal Safety Assessment to reduce risks ship strikes

2.1. An introduction to FSA

The FSA draft guidelines were first adopted by the IMO's Maritime Safety Committee (MSC), at its seventy-fourth session (30 May to 8 June 2001), and the Marine Environment Protection Committee, at its forty-seventh session (4–8 March 2002) [48]. The guidelines have been revised twice since then, the latest revision being in April 2018 [34].

The FSA was drafted to address the four challenges to which any approach to modern maritime safety regulation must respond. It has to be [49]:

- "*Proactive – anticipating hazards, rather than waiting for accidents to reveal them which would in any case come at a cost in money and safety (of either human life or property i.e., the ship itself)*
- *Systematic – using a formal and structured process*
- *Transparent – being clear and justified of the safety level that is achieved*
- *Cost-Effective – finding the balance between safety (in terms of risk reduction) and the cost to the stakeholders of the proposed risk control options*"

IMO envisaged FSA as a tool to help *"in the evaluation of new regulations for maritime safety and protection of the marine environment or in making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational issues, including the human element, and between maritime safety or protection of the marine environment and costs"* [49]. Although the FSA framework was first designed and intended to be used for the evaluation of new or existing regulations, its uses are not limited to the IMO context. FSA follows the essential steps of a risk assessment methodology in line with the ISO 31000:2009, which is to provide principles and generic guidelines on risk management as codified by the International Organization for Standardization (ISO). For a detailed analysis of the Formal Safety Assessment Framework and the latest developments see Kontovas [50] or Kontovas and Psaraftis [51].

The FSA framework is composed of 5 steps that integrate all aspects of potential regulations that are relevant to the shipping industry (Fig. 1):

- Step 1: identification of hazards;
- Step 2: assessment of risks;
- Step 3: risk control options;
- Step 4: cost-benefit assessment; and
- Step 5: recommendations for decision-making.

2.2. Step 1: hazard identification

According to the FSA Guidelines [34], the hazard identification step aims to identify all potential hazardous scenarios, which could lead to significant consequences and prioritize them by risk level. In our case study, the collision event is considered as the main event. Thus, Step 1 aims to identify hazards that contribute the most to the collision. The completion of this step will most probably require the creation of an expert focus group but reviewing the literature and consultations with the industry lead to a first hazard identification. The collision hazards were divided into two main categories (detection failure and avoidance failure) and six sub-categories (see Fig. 2). The list of hazards in those sub-categories, which are briefly outlined below, can be found in the Supplementary Material S1.

- Visual detection failure:

The failure of the crew to detect a whale at the sea surface. These hazards have human or environmental origins. The hazards driven by human factors are related to the competence and the capacity of the crew (e.g., failure to identify visually a whale, inattention due to multitasking, fatigue [11,52–57]). The hazards driven by environmental factors exogenous to the ship. For instance, depending on the areas and the seasons, the whale density varies, and so does the probability of detection. The same observation is true for the different species present, which will impact the probability of detection depending on their behavior (e.g., blow, dive with no fluke, dive with fluke, lunge feeding, resting, surface activity [58]). Meteorological events also impact the detection of whales (e.g., rain, haze, squall [52,55,57–59]).

- Human avoidance failure:

The failure of the crew to avoid a whale despite their effort to do so.

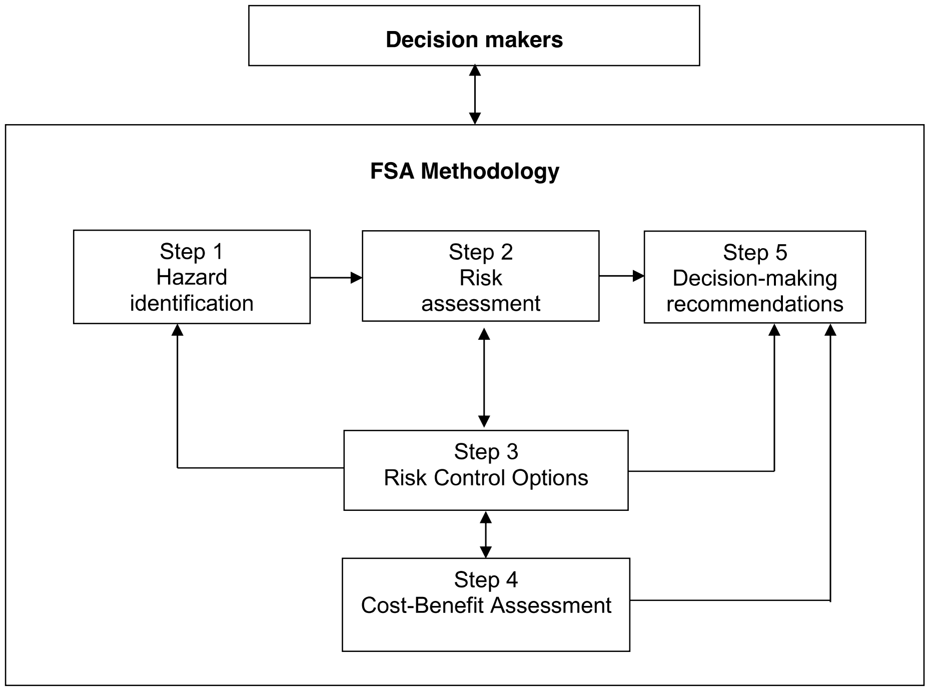

Fig. 1. The Formal Safety Assessment framework (IMO, 2018). *No color should be used in print.*

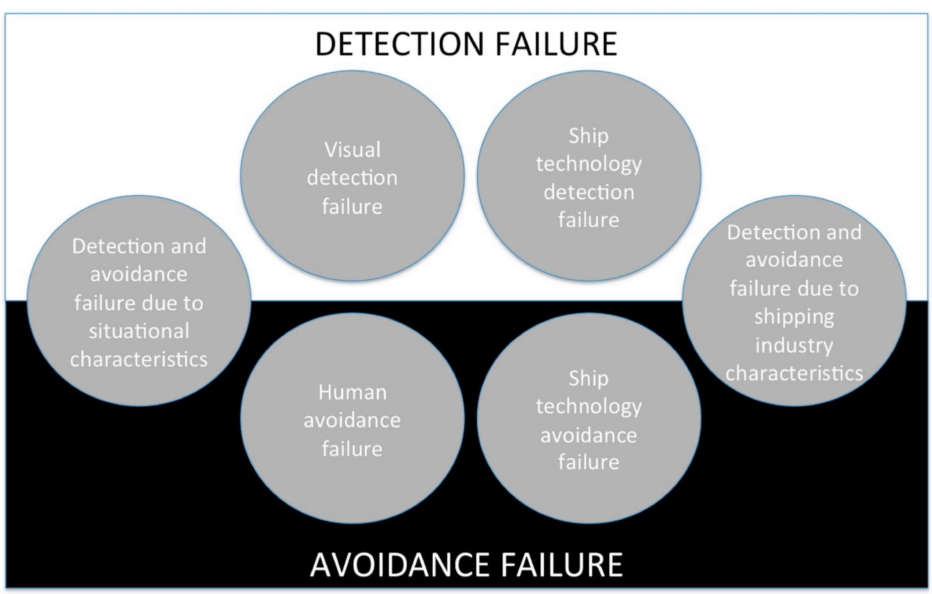

Fig. 2. Contributing events categories and sub-categories. Each sub-category includes contributing hazard to collision with whales. *No color should be used in print.*

Human avoidance can be driven by: hierarchical unwillingness to speak up, lack or inadequate situational awareness or training, lack of master-pilot-master exchanges; inattention due to multitasking [57].

- Ship technology detection failure:

The failure of the shipboard equipment to detect a whale. As the effectiveness of RADAR, sonar, and other devices are limited to detect whales [52], the only technology failures here are dedicated tools to detect whales (e.g., REPCET).

- Ship technology avoidance failure:

The failure of the ship to avoid a whale despite actions taken to do so. Mechanical failure, especially a steering system failure or a complete black-out, may be defined as a hazard although those failures are less frequent in the most recent generations of ships [57]. Other hazards depend on the ship characteristics: turning radius and ship speed [52].

- Detection and avoidance failure due to situational characteristics:

The inability of the crew to engage in avoidance maneuvers due to external factors. This sub-category includes hazards of physical surrounding and policy origin. Physical surrounding factors are linked to external events occurring during navigation: density of maritime traffic, close proximity of anchorages and harbor areas, proximity of navigational hazards (e.g., shoal), mix of maritime traffic, limited sea room (choke points), traffic congestion. Policy factors are linked to TSS and precautionary area, marine safety information, and navigation rules (COLREG) [57,60–62].

- Detection and avoidance failure due to shipping industry characteristics:

The commercial pressures preventing the crew from engaging actions to minimize the collision risk. Some of the hazards are internal to the company, such as pressures to arrive on time or other constraints (e.g., minimization of fuel consumption and air emissions) [57,63]. Those hazards are most of the time linked to some marine policies which compel the company to comply (such as the Sulphur Emission Control Areas – SECA or mandatory speed limits) [57].

As mentioned before, each of these hazards needs to be validated and ranked. To achieve the latter, the use of the qualitative Delphi method can be utilized to reach a consensus [34,51]. The biggest challenge is the lack of data regarding how these factors affect whale collisions. While the identification of hazards is reasonably straightforward in the literature, their contribution is hard to estimate. This difficulty lies in the fact that ships rarely notice the collision with a whale, and when they do, it often goes unreported [53,64–69].

2.3. Step 2: risk analysis

According to the FSA Guidelines [34], the risk analysis step aims to obtain a quantitative measure of the probability of occurrence of risk contributors and an evaluation of the potential consequences associated with the identified hazards in the previous step. Usually, the applications of FSA focus on events such as ship-ship collisions, groundings, fires/explosion [70–72] for which there are available casualty databases. For example, the IHS Sea-web Casualties database (formerly known as Lloyd's Register-Fairplay) and Lloyd's List Intelligence Casualties Service are fairly complete and can be used to provide a probability of hazards occurrence [73,74]. Data on collisions between whales and ships are less well organized. While the IWC maintains a database of most of the proven whale collision events, several other published databases provide additional or complementary data [64,65]. Nevertheless, those databases do not have a lot of recorded events in comparison to other casualty databases. A review of the IMO casualty database (1997–2018) finds that no events were recorded as "Undefined" or "Contact". "Contact" data reflect events of "*striking or being struck by an external substance but not another ship or the sea bottom*". The same inquiry needs to be achieved in Lloyd's database to assess its content. Other relevant data can also be investigated in the national marine mammal stranding networks databases. Despite the existing databases, most of the whale collisions go unnoticed due to the low detection rate [52,58]. Indeed, the small percentage of dead whales that strand and the decomposition state of the related carcasses often prevent the identification of the mortalities induced by collisions [65,75–77].

An adaptation of the FSA risk analysis is needed to account for the lack of data issue. Over the past decades, ship-whale collision risk analyses have evolved from simplistic approaches to more complex ones, which are outlined as follows (see also Table 1 for a summary):

- Approach A: human-induced direct mortality

Approach A is used in the case where AIS data and abundance data are not available. In the absence of these data, the stranding data from the national stranding data networks are here used. The relation between stranding or drifting carcasses and causes of mortality in the stranding data is used in combination with a natural mortality rate to assess a carcass detection rate depending on the whale species [78–80]. The number of dead whales due to collisions is assessed using this rate [15]. Due to the heterogeneity of the data gathered by the stranding networks [6], the calculated risk from this approach will most likely be underestimated. This approach allows an assessment at the whale population's home range scale, but also at a smaller scale. Nevertheless, the precision of this approach can decrease depending on the scale of the study site, as carcasses can drift outside or inside the study site [81]. The main advantages of this approach are that it does not need a lot of data and is thus not expensive.

- Approach B: collision indicator

Approach B is used in the case where AIS data and abundance data are partially available. Whale abundance and ship density are used to extract status indicators that are overlapped in order to assess the risk of collision [82]. For this approach, the collision risk analysis model of Martins et al. [82], seems to be the most suited option given its holistic approach. Martins et al. [82], defined the risk of collision indicators as the sum of value attributed to the whale density and the shipping density. To be noted that whale density indicator can be defined either from whale calculated density [83,84] or expert judgment density [85]. While more precise than Approach A, this approach has the disadvantage of requiring a more significant amount of data, involving a higher cost of implementation. Despite its simplistic semi-quantitative methodology, this approach was only developed a few years ago, after approach C.

- Approach C: lethal collision probability

Approach C is used when both AIS data and abundance data are available. Two types of models have been integrated into this approach. First, the quantitative probability of a collision between a ship and a whale is investigated [21]. Then, the main assumption that ship speed is directly linked to the probability of mortality is integrated into models [12,80]. Hence, unlike Approach B, this approach addresses quantitatively both the frequency and the severity of a collision. Lately, models were spatialized and upscaled to cover larger areas and integrate a more holistic approach (Fig. 3 [69,86,88]). Approach C has the advantage of having a higher grid resolution and a more precise level of risk, as the density of ships is available quantitatively, whereas approach B qualitatively grades the density. This higher resolution comes at a higher cost.

The most critical challenge in the Risk Analysis Step is to define the level of risk that is acceptable to the regulators or the society. It is obviously difficult to estimate the risk based on each approach, but it is even more challenging to determine whether this level of risk is acceptable, e.g., mitigation measures are needed, or not. Indeed, the impact of a collision needs to be assessed at a population level and not at the individual whale level. Indeed, the cumulative effect of whale deaths matters. In other words, the death of 10 whales due to collisions might

Table 1
Characteristics of existing collision risk assessment approaches.

Type of risk assessment	Output			Characteristics			Primary source
	Frequency of collision	Severity of collision	Output example	Price	Precision	Amount of data needed	
Approach A	Yes	Yes	Number of lethal collisions	Low	Low	Low	[15]
Approach B	Yes	No	Collision risk indicators	Medium	Medium	Medium	[82]
Approach C	Yes	No	Probability of collisions	High	High	Medium	[88]
	Yes	Yes	Probability of lethal collisions	High	High	High	[21]

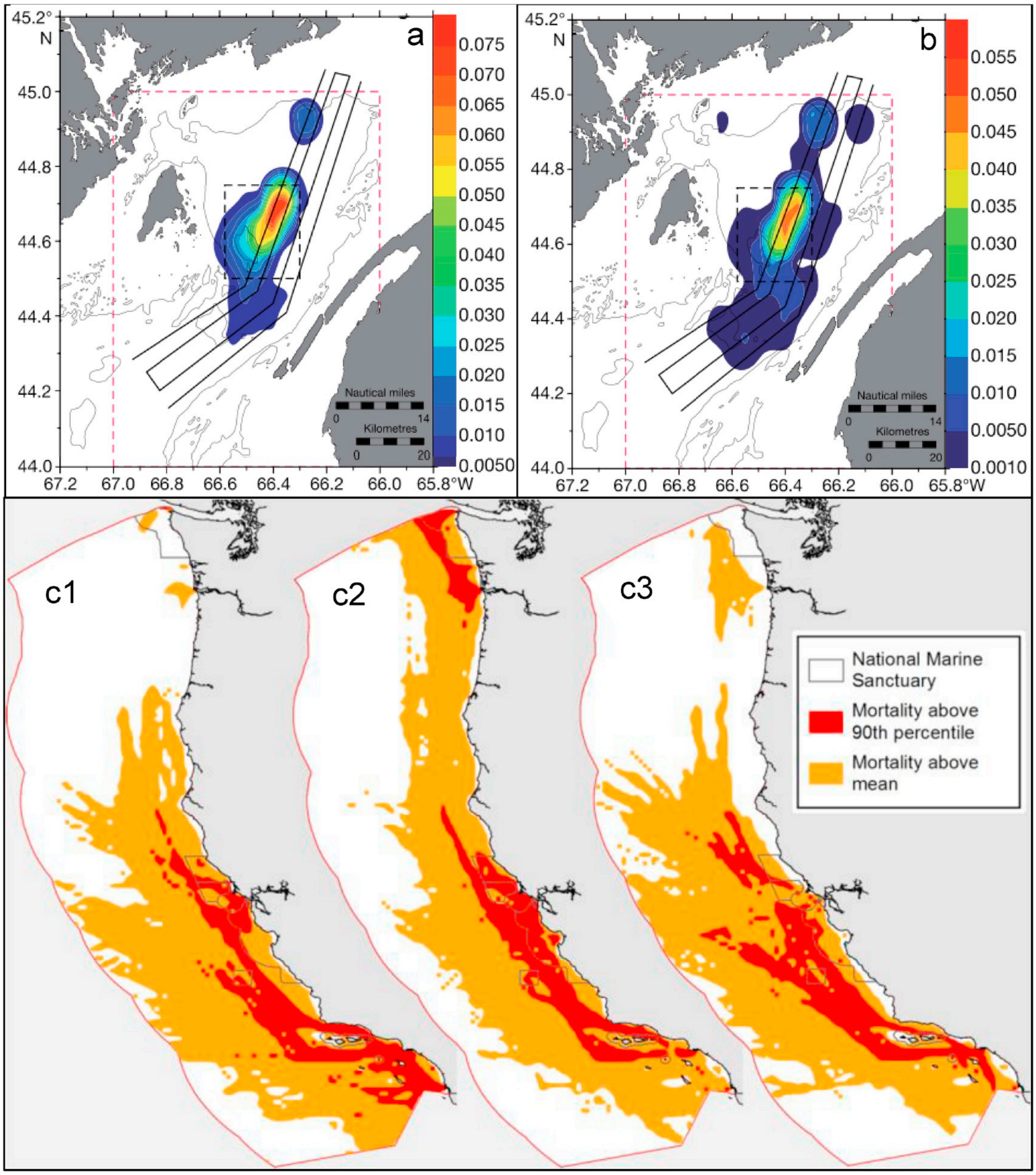

Fig. 3. Assessment of the ship-right whale encounter risk (a), the lethal collision risk (b) at small scale (Bay of Fundy, Canada; Vanderlaan et al., [87], © Inter-Research 2008) and the lethal blue (c1), humpback (c2) and fin whales (c3) at large scale (US West Coast; Rockwood, Calambokidis and Jahncke [69]). *No color should be used in print*

not impact a population, but 20 deaths might lead to a decline of this population. To define the severity, a population viability analysis (PVA) can be adapted to do this assessment. A PVA is a process aiming to evaluate the likelihood that a population will persist in the future [89]. To be noted that in some areas, the gap of knowledge on the whale population or the lack of financial support might limit the effectiveness the PVA implementation [90,91]. In those cases, the IMO guideline allows the intervention of experts to define the risk qualitatively, but advocate for a transparent methodology [34].

In line with the FSA framework, an adaptation of the As Low As Reasonably Practicable (ALARP) concept could be used to incorporate PVA [92]. ALARP arises from UK legislation, particularly the Health and Safety at Work etc. Act 1974, which requires "*Provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health*". According to this framework, there are three categories of risk tolerance: Unacceptable Risk, ALARP, and Acceptable Risk. Unacceptable Risk (for example resulting from a high accident frequency and a high number of fatalities) should either be forbidden or reduced at any cost. Between this Unacceptable Risk and the Acceptable Risk (where no action to be taken is needed), the ALARP range of risk is defined. In this range, the risk should be reduced until it is no longer reasonable (i.e. economically feasible) to reduce the risk.

Here, the paper proposes the ALARP range of risk using Limit Reference Points (LRP) in the calculation of PVA to set boundaries of tolerable risk and assess the threshold risk of collision. Limit Reference Points (LRP) provide an assessment of the number of individuals that can be removed from the population without threatening its survival [93]. Fig. 4 illustrates a possible adaptation of the ALARP approach, using two LRPs of different level of objective: "2% criterion" [94,95] and Potential Biological Removal (PBR [96,97]). Other approaches can be investigated, such as the adaptation of the concept of "No Net Loss" [98].

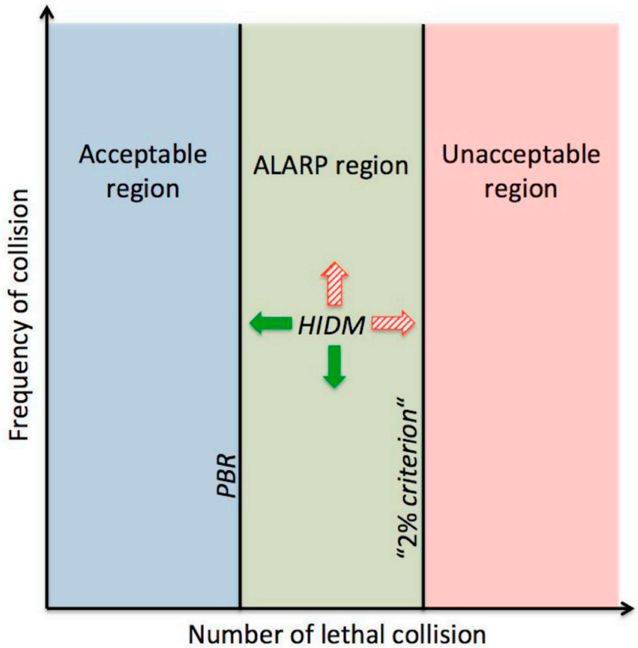

Fig. 4. Possible adaptation of the As Low As Reasonably Practicable (ALARP) approach to the whale-ship collision issue, bounded by the Potential Biological Removal (PBR) and the "2% criterion". Green arrows represent positive evolutions of the HIDM related to collisions and red striped arrows negative ones. Adapted from Ref. [92]. *No color should be used in print*

2.4. Step 3: risk control options

According to the FSA Guidelines [34], the purpose of Step 3 is to propose effective and practical Risk Control Options (RCOs) comprising the following four principal stages:

- *"Focusing on risk areas needing control;*
- *Identifying potential risk control measures (RCMs);*
- *Evaluating the effectiveness of the RCMs in reducing risk by re-evaluating step 2; and*
- *Grouping RCMs into practical regulatory options."*

Thus, one of the first tasks in Step 3, is to identify measures that reduce the risk of whale collisions based on the top hazards that have been identified in Step 1. These measures are called Risk Control Measures (RCM) in the FSA terminology. RCMs can either prevent, mitigate, or reverse the impacts of the top hazards. They are discussed in the expert focus group to assess their effectiveness. A lack of data is, again, an obstacle that can be overcome through expert judgment. For each of key RCMs, Step 2 is repeated to assess the potential risk reduction induced. More than one RCM can be combined into groups which are referred to as Risk Control Options (RCO) [34,50].

Several RCMs have been identified in the literature and consist of either operational or technical measures. Operational RCMs (ORCM) are usually related to the way that ships should be operated. In most cases, voluntary or mandatory navigation recommendations are implemented, such as reducing the operational speed in specific areas or traffic management route systems (see Table 2). Technical measures (TRCM) are control measures that aims to better detect whales (see Table 3). They provide information on the location of whales or on the location of whale high-density areas. TRCMs can provide information to mariners that may lead to the more efficient implementation of ORCMs. For example, the Boston passive acoustic network (TRCM-6) is synchronized with ORCM-8 and ORCM-11 [99,100].

The most critical process in Step 3 is the evaluation of the effectiveness of each measure to reduce the risk of ship strikes. In the literature, most of the assessments are ex-ante analyses that process either the compliance or the risk reduction induced (see Supplementary Material S1 and also [11,122]). However, some studies have analysed both parameters.

First, some ex-ante studies used theoretical full compliance with RCMs from the shipping industry to study the risk reduction induced. In those cases, the risk reduction induced can vary from low to high value (see Table 4). Usually, SR measures tend to have a lower impact on the risk of collision than TSS measures. Second, regarding post ante analyses, the compliance does not seem to be linked to the mandatory status (Table 4). To be noted that in some cases, low compliance involves an equivalent risk reduction than high compliance (ORCM-15 vs. ORCM-2). Further, the effectiveness of a solution may vary between the time of implementation and the years that follow, as it was exhibited in several studies (e.g., ORCM-2, ORCM-16, ORCM-17 [111,123]). The effectiveness of TRCMs varies too much to require an extensive literature review in this paper. For more information on TRCMs effectiveness, the interested reader can refer to the work of Silber, Bettridge, and Cottingham [52].

The efficiency of the RCO/RCM depends on several parameters: its best-case effectiveness to reduce the risk, and the stakeholders' compliance, which in turn depends on the broad costs and benefits of implementation, the regulatory status associated with the RCO/RCM (e.g. mandatory or voluntary), and the vigorousness of enforcement [124–126]. The efficiency of RCOs/RCMs is often debated in the literature. While models may help to evaluate the effectiveness of a solution, this is generally under the assumption of full compliance from the shipping industry, which is the theoretical best-case scenario [87,101,

Table 2
Existing or tested Operational Risk Control Measures to avoid whale collisions.

Code	ORCM	Spatial status	Temporal status	Legislative status	For example
ORCM-1	Speed Reduction (SR)	Fixed	Temporary	Mandatory	[101]
ORCM-2	Speed Reduction (SR)	Fixed	Temporary	Voluntary	[102]
ORCM-3	Speed Reduction (SR)	Fixed	Fixed	Mandatory	[103]
ORCM-4	Speed Reduction (SR)	Fixed	Fixed	Voluntary	[17]
ORCM-5	Speed Reduction (SR)	Dynamic	Dynamic	Voluntary	[100]
ORCM-6	Speed Reduction (SR)	Fixed	Dynamic	Mandatory	[104]
ORCM-7	Traffic Separation Scheme (TSS)	Fixed	Temporary	Mandatory	[105]
ORCM-8	Traffic Separation Scheme (TSS)	Fixed	Temporary	Voluntary	[19]
ORCM-9	Traffic Separation Scheme (TSS)	Fixed	Fixed	Mandatory	[106]
ORCM-10	Traffic Separation Scheme (TSS)	Fixed	Fixed	Voluntary	[107]
ORCM-11	SR and TSS	Fixed	Temporary	Voluntary	[108]
ORCM-12	SR and TSS	Fixed	Fixed	Mandatory	[109]
ORCM-13	SR and TSS	Fixed	Fixed	Voluntary	[110]
ORCM-14	Area To Be Avoided (ATBA)	Fixed	Temporary	Voluntary	[23]
ORCM-15	Area To Be Avoided (ATBA)	Fixed	Fixed	Voluntary	[108]
ORCM-16	SR and ATBA	Fixed	Temporary	Voluntary	[111]
ORCM-17	SR, TSS, and ATBA	Fixed	Temporary	Voluntary	[111]

Table 3
Technical Risk Control Measures to avoid whale collisions.

Code	TRCM	Examples of implementation/test	For example
TRCM-1	Right Whale Sighting Advisory System	US waters	[27]
TRCM-2	REPCET	Pelagos and Agoa Sanctuaries	[25]
TRCM-3	Whale Alert	US waters	[112]
TRCM-4	Visual detection (dedicated)	Boston	[56]
TRCM-4	Tagging and telemetry	*Theoretical*	[52]
TRCM-6	Passive acoustics	Boston	[52]
TRCM-7	Ship mounted passive acoustics	France	[113]
TRCM-8	Active acoustics	*Theoretical*	[52]
TRCM-9	Radar	Australia	[114]
TRCM-10	Infrared	Australia	[115]
TRCM-11	Predictive modeling	California (US)	[116]
TRCM-12	Sonar	Hawaii (US)	[117]
TRCM-13	US Navy Sound Surveillance System	Washington (US)	[118]
TRCM-14	Acoustic Harassment and Deterrent Devices	Bay of Fundy (Canada)	[119]
TRCM-15	Night scope	US waters	[119]
TRCM-16	Satellite imagery	*Theoretical*	[52]

106]. The FSA proposes a framework where all parameters can be processed in an interdisciplinary approach [32]. As the efficiency is difficult to be accurately quantified, the transition from effectiveness to efficiency as a measure of outcome is often accomplished by calculating a cost-effectiveness proxy [127] that is discussed, among others, in Step 4.

2.5. Step 4: assessing the costs and benefits

According to the FSA Guidelines [34], the purpose of Step 4 is to identify and compare the benefits and costs associated with the implementation of each RCO identified and defined in Step 3. A cost-benefit assessment may consist of the following stages:

Table 4
Compliance and risk reduction induced by various operational RCMs.

Code	ORCM	Legislative status	Compliance (%)	Risk reduction induced (%)	For example
ORCM-1a	SR	Mandatory	75	38.5	[101]
ORCM-1b	SR	Theoretical	100	7.5–52	[109]
ORCM-2	SR	Voluntary	72	35–40	[123]
ORCM-3	SR	Theoretical	100	3.7–56.7	[103]
ORCM-8	TSS	Theoretical	100	10–32	[19]
ORCM-9	TSS	Theoretical	100	94.8	[106]
ORCM-10	TSS	Voluntary	96.2	54.3	[101]
ORCM-12	SR and TSS	Theoretical	100	69–75	[109]
ORCM-14a	ATBA	Voluntary	71	82	[22]
ORCM-14b	ATBA	Theoretical	100	39	[21]
ORCM-16	SR and ATBA	Voluntary	9.3	28–34	[111]
ORCM-17	SR, TSS and ATBA	Voluntary	9.7–11.2	36–40	[111]

- "*Consider the risks assessed in Step 2, both in terms of frequency and consequence, in order to define the base case in terms of risk levels of the situation under consideration;*
- *Arrange the RCOs, defined in Step 3, in a way to facilitate understanding of the costs and benefits resulting from the adoption of an RCO;*
- *Estimate the pertinent costs and benefits for all RCOs;*
- *Estimate and compare the cost-effectiveness of each option, in terms of the cost* per *unit of risk reduction by dividing the net cost by the risk reduction achieved as a result of implementing the option; and*
- *Rank the RCOs from a cost-benefit perspective in order to facilitate the decision-making recommendations in Step 5 (*e.g., *to screen those which are not cost-effective or impractical).*"

2.5.1. The cost-effectiveness analysis

The cost and benefit values associated with an RCM have to be combined with the risk reduction to assess the costs and the benefits per percentage of risk reduction [34]. Until recently, this step was focusing mainly on human safety. There are several indices, which express cost-effectiveness depending on the safety of life such as Gross Cost of Averting a Fatality (Gross CAF) and Net Cost of Averting a Fatality (Net CAF) as described in the FSA guidelines. The numerator of the Net CAF integrates the benefit, whereas the Gross CAF does not. Hence, Net CAF is much more adapted to environmental issues, as other benefits such as avoiding environmental damages could be considered.

Since 2006, the FSA framework has opened up to the analysis of risk evaluation criteria for accidental releases to the environment, and specifically for releases of oil. Discussions on this matter were sparked to a significant extent by EU research project SAFEDOR [128], which defined the criterion of CATS (Cost to Avert one Tonne of Spilled oil) as an environmental criterion equivalent to CAF [129]. Even though the FSA guidelines only include provisions to assess the environmental damages from oil spills [63], other risk acceptance criterions have been developed and considered for FSA application through recent years [130]. These criterions are mainly focused on air emission, but encourage researches to built relevant criterions for risk assessments, as advocated by the FSA guidelines [34].

In order to assess risk reduction measures related to ship collisions with whales, by using the FSA framework, there is a need to define an index *"in terms of the cost* per *risk reduction unit by dividing the net cost by the risk reduction achieved as a result of implementing the option"*. For ship strikes, our study, therefore, proposes a similar cost-effectiveness index, named Net Cost to Avert a Whale Fatality (NCAWF), as follows:

$$NCAWF = \frac{\Delta C - \Delta B}{\Delta R}$$

where ΔC is the cost per ship of the RCO under consideration; ΔB is the economic benefit per ship resulting from the implementation of the RCO; ΔR is the risk reduction depending on the number of fatalities averted, induced by the RCO. Note that the risk reduction ΔR is assessed in Step 3.

The costs and benefits should cover the entire lifetime of the measure and anticipate the potential future modification of the context [34]. For example, a change can appear in whales habitat use or abundance, or even in shipping traffic (e.g., volume, port) [131,132]. These changes, which can be, or not related to the RCO implemented, need to be anticipated as well as possible. Several costs and benefits components come into play. Identified costs and benefits include:

- The costs to implement the measure, which could include capital expenses [129];
- The costs of maintenance [133];
- The costs of operation, direct or indirect ones, as the fuel consumption or costs associated with delays in the time of arrival [52,122];
- The benefits to avoid costs such as the repair costs after a collision or a ship loss [59,64,65], which may be calculated by using historical data.

2.5.2. The cost-effectiveness criterion

One of the underlined principles of FSA is that the decision-makers (Step 5) should be provided with recommendations of measures to reduce the risk that are cost-effective. In order to do so, a cost-effectiveness criterion should be used. To recommend an RCO for implementation, the cost-effectiveness index must be less than the cost-effectiveness criterion; otherwise, the RCO is rejected by the IMO. The cost-effectiveness criterion definition varies depending on the risk evaluated. It usually takes into account the following approaches [134,135]:

- "*Observations of the willingness to pay to avert a fatality;*
- *Observations of past decisions and the costs involved with them;*
- *Consideration of societal indicators.*"

The dominant yardstick in all FSA studies that have been submitted to the IMO so far is the so-called "$3 m criterion". This criterion is to cover human fatalities from accidents and implicitly, also, injuries or ill health from them. This criterion was calculated using the third approach [136–138]. Indeed, the human safety criterion was inspired by the Life Quality Index, which takes its origin in a combination of life expectancy, wealth, and health indicators [139]. For environmental safety, the second and third approaches are usually used [36,130]. For example, the criterion for the oil spill issue was calculated in function of the rescue and clean-up costs of historical events (2nd approach), whereas for carbon dioxide, its calculation was in function of the IPCC 2030 target (3rd approach) [129,140].

In the literature, there is currently no cost-effectiveness criterion to assess risks to whales. In our opinion, a combination of the second and third approach could be used. Indeed, for societal indicators (3rd approach), the cost of losing a whale can be looked into. Several approaches can be used and combined to achieve this assessment. First, contingent studies on the willingness to pay to protect whales can be done [141–145]. These studies are nevertheless costly and time-consuming [146]. One way to overcome these constraints is through a benefit transfer study using willingness to pay value from original studies [147–150]. Unfortunately, these kinds of studies suffer from different biases that tend to cause variation in results, related to factors such as methodology, location, species concerned, resident status, payment vehicle and frequency [151]. Second, whales are since a few decades considered as biodiversity services as non-consumable direct use-value (e.g., whale watching). Using whale watching revenues [152,153], the calculation of the lifetime value of a whale can lead to the assessment of the cost of losing a whale [154]. Finally, a market approach has emerged recently [155], although highly discussed [156–158].

As attributing a monetary value to biodiversity is increasingly criticized [156,159–161], a multi-criteria analysis can also be considered as a new approach to assess the IMO criterion [162]. A multi-criteria analysis (MCA) is a decision-making approach combining conflicting ecological, social, political, and economic targets. The advantage of this approach is to integrate into the analysis the provisioning, regulating, and supporting services provided by whales [163–165]. Indeed, these services are most of the time not taken into consideration, as their monetary valuation is often not possible [166]. Similarly, ecological values can be considered as whales can act as ecosystem engineers or key species of ecosystem functioning [163,164]. Other dimensions could be integrated, using social indicators (e.g., reputational risk, proactive action [30,167]). An MCA allows different languages of valuation to be used as indicators of each target [168]. Hence, a global valuation does not emerge from this approach, but an assessment of the cost and benefit can be put in perspective of other proposed solutions to mitigate the issue. Recently, different frameworks, that can be adaptable to the whale issue, emerged to value the marine ecosystems and biodiversity [169–172]. However, the MCA approach is outside the FSA guidelines and would imply an important change in the FSA framework.

Regarding past decisions and the costs involved with them (2nd approach), the cost of carcasses management can be looked into, even though the fact that the cost is rarely paid by the shipping industry (Tab. 6). For example, in France, the management of stranded carcasses is handled by the government, or by the harbor when a whale is stuck on a ship bow [59,173]. For the latest, some shipping industries insurance (P&I) may pay for carcass management. The cost of carcass management is variable depending on the countries. In some countries, the carcass is not processed and left to decomposition [174]. In others, the carcass is managed through knackery, explosion or submersion (e.g., in France with a cost between $28,000 and $89,000 ($US_{2016}$)) [173,174]. For those countries, the second approach may be considered.

To summarise, as per the FSA Guidelines, the output from Step 4 comprises of the following:

- Costs and benefits for each RCO identified in Step 3;
- Cost-effectiveness index, representing the cost per unit of risk reduction; and
- Cost-effectiveness criterion, to be compared to the cost-effectiveness index for decision-making.

To be noted that the mathematical equivalency between the cost-effectiveness analysis, as used within the FSA, and the classical cost-benefit assessment has been shown when using a cost-effectiveness criterion [50]. The most challenging process is to monetize benefits, especially the environmental ones. This step will most likely require the use of an economic value to quantify the benefit of avoiding a whale fatality. The above discussion exposed research angles that can be explored to achieve this challenging valuation.

2.6. Step 5: recommendation for decision-making

The final Step of FSA aims at giving recommendations to the decision makers for safety improvement, taking into consideration the findings during all four previous steps. The RCOs that are being recommended should reduce the risk to the "desired level" and be cost-effective [50]. To this extent, there is a need to define the desired or acceptable level of risk and clear cost-effectiveness criteria. According to the Guidelines, the purpose of this Step is to define recommendations, which should be presented to the decision-makers in an auditable and traceable manner. Note that the RCOs that should be proposed for implementation will be recommended by the decision-maker, in the case of FSA, this should be the IMO after receiving recommendations from a group of independent experts. The recommendations would be based upon the comparison and ranking of all hazards; the comparison and ranking of risk control options as a function of associated costs and benefits; and the identification of those risk control options which keep risks as low as reasonably practicable (see the notion of ALARP in Section 2.3).

3. Conclusions and future research

Human activities induce or amplify threats to survival for some whale populations. Although there are limited data on the various causes, ship collisions are known to be major threats to whales [6,18]. A variety of approaches have been considered to reduce this threat. These include operational measures such as mandatory speed reduction or technical ones, such as detection tools. There is, however, a lack of tools to systematically assess the various measures that can reduce the risk of ship collisions with whales. This impedes decision-makers recommendations, government enforcement, or industries willingness to act [24, 126,175–177]. Recent papers highlighted the potential improvement in collision management that can be offered by the IMO [175,178].

Therefore, this paper proposes a holistic approach through a risk assessment framework that has been adopted by the IMO, namely the FSA. The objective of this paper is to conceptualize the use of the FSA to address collisions between ships and whales. There are, however, many challenges in using FSA to assess measures that can reduce the risk of ship strikes.

First, there is a lack of casualty data that can be used to identify the major hazards (Step 1). Most of the whale collisions go unnoticed due to the low detection rate, although some events have been identified in the literature [52,58]. Despite the limited data, by reviewing the literature and through consultation with the industry, this paper presents the major collision hazards, which have been divided into two main categories (detection failure and avoidance failure) and six sub-categories, see Fig. 2 for more.

Second, there is a need for standardization of the risk analysis methods to estimate quantitatively the frequency and the consequence of collision (Step 2). There is actually a good basis for future research; see the vast amount of papers on this area as presented in Section 2.3. Indeed, numerous studies, on the probability of encounter between a ship and a whale [15,21] and its consequence (i.e., the probability of whale mortality), expressed in most cases as a function of the ship speed [12,69,80], can be used in Step 2. Nonetheless, the most critical challenge though in this step is not the evaluation of the risk but to define the level of risk that is acceptable to the regulators or the society. What level of risk is acceptable? How many deaths of whales are acceptable? These are very tough moral questions to be asked. This paper does not approach risk acceptance at an individual level, but rather at a population level. Our approach uses the notion of Limit Reference Points (LRP), which is an assessment of the number of individuals that can be removed from the population without threatening its survival. A first approach using the ALARP notion is introduced, but most research is required in this area. Alternatives such as the "No net loss" approach could be investigated [98].

Finally, the biggest challenge lies in Step 4. The FSA calls for a cost-effectiveness analysis to be performed. The paper has therefore presented an index, which is defined as Net Cost to Avert a Whale Fatality (NCAWF). The main challenge is to monetize the benefits for risk reductions, as this in one way or another requires monetizing the benefit of protecting a whale. Attributing a monetary value to biodiversity is increasingly criticized, but the paper nevertheless presents in Section 2.5 (see also Table 5) some proposals for such a value. This is the first approach to an area that requires further research.

Furthermore, the FSA is a lengthy and potentially expensive process, which might not be sufficient in some situations, especially in critical situations. The above steps, and especially the ones related to thresholds, need to be carefully looked at in cases where urgent actions are required, i.e., in crisis management. For example, the North Atlantic right whale is one of the world's most endangered large whale species. In 2017, the mass mortality of this species occurred in Canadian waters over a 3 month period [179]. Stringent risk tolerance limits (e.g., risk tolerance for killing right whales near to zero), and the implementation of very costly policy measures were needed to tackle this issue. Our approach could work in crisis situations by having very low-risk acceptance limits and at the same time setting higher cost-effectiveness criteria.

To sum up, this paper conceptualizes the use of a systematic decision-making methodology, namely the FSA, to assess the risks of ship strikes. The paper highlights the main areas in the methodology that need to be further addressed, and at the same time, summarises our findings of the major hazards, as well as, the main risk control measures that have been adopted by various national and international regulators. It is hoped that this work could spark further research in this area, which could lead to more transparent and systematic assessment of the risks related to collisions between ships and whales, and help propose cost-effective measures to reduce the related risks. In the end, this approach may lead to the emergence of control options that take into consideration both whale conservation and maritime traffic stakes, contributing to a better compliance of the shipping industry to those options.

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Appendix A. Supplementary data

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