An interdisciplinary approach to the management of whale-ship collisions

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"Scientific research was much like prospecting: you went out and you hunted, armed with your maps and instruments, but in the end your preparations did not matter, or even your intuition. You needed your luck, and whatever benefits accrued to the diligent, through sheer, grinding hard work."

Michael Crichton, "The Andromeda Strain", 1969

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FOREWORD

The thesis manuscript is written in English. This manuscript is based on five research articles published or produced for publication in international peer-reviewed journals. The correspondence between the research articles and the manuscript chapters are outlined in section *"Scientific production"*. The articulation between chapters/research articles is done in sections *"Introduction"* and *"Discussion"* to ease the reading of the manuscript. A separate section at the end of the manuscript lists all the thesis references.

This work was supported by the *"Laboratoire d'Excellence"* LabexMER (ANR-10-LABX- 19) at the European Institute of Marine Sciences (IUEM), by the Région Bretagne, and by the University of Western Brittany through an allocation to the Doctoral School of Marine and Coastal Sciences.

ABSTRACT

Since the whaling moratorium, novel threats to whale's survival emerged. Conservation scientists are particularly concerned by the collision between whales and ships. The whale-ship collision threat is ever growing with the expansion of maritime traffic and the establishment of new roads. Some whale populations are declining due to this threat, such as the Mediterranean fin whales (*Balaenoptera physalus*) and sperm whales (*Physeter macrocephalus*) populations – which will be taken as a case study for this thesis dissertation.

Several solutions do exist to reduce whale-ship collisions, but the shipping industry's compliance with these solutions is often low. Consequently, the applied effectiveness of these solutions is hampered. The first stages of the thesis identified two primary features explaining the lack of compliance: (1) the lack of systemic approach to whale-ship collision risk management; and (2) the non-integration of economic and logistic dimensions in it. These prevent the decision-makers from having a transparent overview of the issue, which is decisive to recommend solutions.

The research question emerged from these initial findings: How should human and ecological dimensions be integrated into a standard process to improve the management of whale-ship collisions? Following this question, the dissertation objectives were developed: (1) to define a standardized assessment process for mitigation solutions; (2) to investigate the economic and logistic dimensions required to achieve a holistic assessment of the whale-ship collision issue.

We studied the decision-making tools of the International Maritime Organization (IMO), which is the United Nations organization that deals with all aspects of maritime safety and the protection of the marine environment. From our investigation, the Formal Safety Assessment (FSA) framework emerged as a potential process for managing the whale-ship collisions at the international level. 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*. The FSA is composed of the following steps: (1) identification of hazards; (2) assessment of risks; (3) risk control options; (4) cost-benefit assessment; and (5) recommendations for decision-making. These steps are investigated in this thesis to define their limitations to the whale-ship collision issue, and to study ways to overcome these limitations.

Among these limitations, the economic dimension is rarely integrated when introducing mitigation solutions to whale-ship collisions. The economic benefits of avoiding whales have not

been studied in the literature, as there are suspected low for the shipping industry. We proposed in this thesis a first quantification of the probability of ship damage subsequent to a whale-ship collision. Overall, one out of ten collisions with whales leads to ship damages. Repair costs can reach hundreds of thousands of dollars, and income losses are hypothesized to be higher than the costs of repair.

While economic impacts are pivotal to understand the low compliance of the shipping industry, logistical aspects should not be underestimated. We thus performed one of the first inquiries into the shipping industry preferences to better understand the lack of compliance with mitigation solutions. This investigation showed, amongst others, a preference to avoid instead of reducing the speed in high-density whale areas, especially in coastal waters. Our results could be integrated as guidelines for the selection of whale-ship collision mitigation solutions.

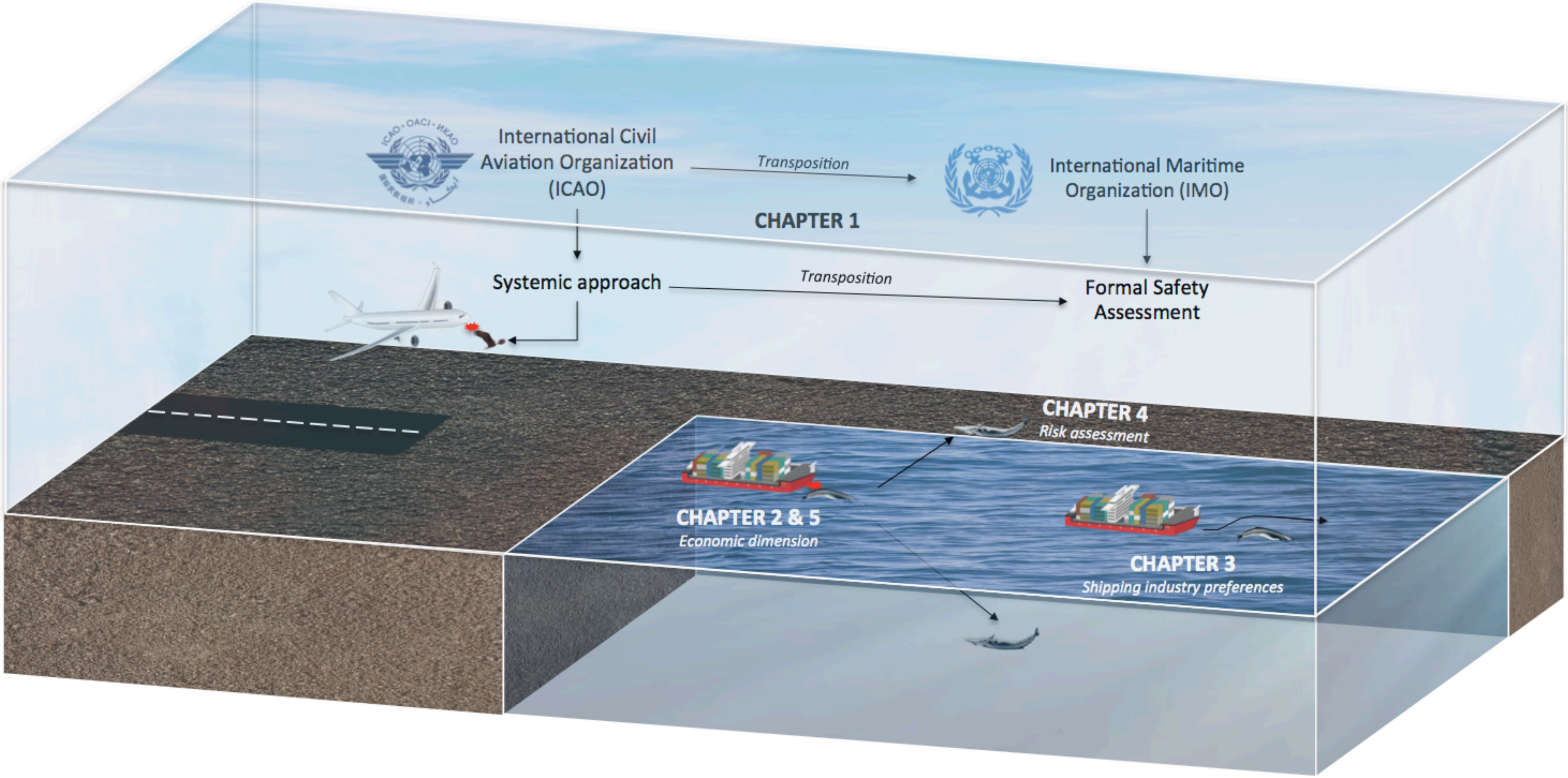
In a systemic approach, it is crucial to compare the economic and logistic dimensions with the ecological risk to help decision-making. While the quantifying of the whale-ship collision risk is challenging, we proposed to estimate the severity of the Human-Induced Direct Mortality (HIDM) on the Mediterranean sub-populations – in a data-poor environment. Our results highlighted the need to revise the ACCOBAMS established management rule and confirmed the need to revise the fin whale IUCN status to a more endangered category.

Once the economic and ecological aspects of the whale-ship collision issue are known, decisions on the implementation of solutions can be taken. To help with this decision, within the cost-benefit step of the FSA, the trade-off between costs and benefits is often compared to a risk evaluation criterion. This criterion is used to assess if the costs are disproportionate in comparison to the risk reduction induced. We defined the cost of averting a whale fatality and its application as a risk evaluation criterion. Our findings show that the IMO would recommend the Mediterranean REPCET solution if the criterion were used.

The thesis dissertation explored axes of research towards systemic approaches, which can also be used outside the scope of the FSA (e.g., Particularly Sensitive Sea Areas, proposals to Marine Environment Protection Committee). The economic integration for whale-ship collision management – which is poorly processed in the literature – allows potentially more transparent proposals. Our findings improve the mutual comprehension between conservationists and shipping industry stakeholders, and tend towards improving whale conservation.

Key words: whale-ship collision; International Maritime Organization; Formal Safety Assessment; risk assessment; logistical preferences; maritime economics; avoided costs; cost-effectiveness; risk evaluation criterion.

GRAPHICAL ABSTRACT



Conception: Sèbe and Guillou.

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PUBLICATIONS IN PREPARATION (soon to be submitted)

Sèbe, M., Nassiri, A., Pendleton, L. An assessment of the shipping industry's preferences for whale-ship collision mitigation solutions.	Chapter 3
Sèbe, M., Gourguet, S. Whale-ship collision dynamic and management. Lessons learned from other wildlife-vehicle collisions.	Introduction; Conclusion; Annex 3

PUBLICATIONS IN PREPARATION (in progress)

Sèbe, M., Gourguet, S., Pendleton, L., Grose, S., Madon, B. Whale Human-Induced Direct Mortality in Mediterranean sub-populations: How much is too much?	Chapter 4
Sèbe, M., Kontovas, C.A., Gourguet, S., Pendleton, L. Risk evaluation criterion: Evaluation of measures to reduce ship strikes – A Mediterranean case study.	Chapter 5

CONFERENCE

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INTRODUCTION

"Risk management is a balancing act."

J.S. Nathwani, N.C. Lind, and M.D. Pandey, 2012

INTRODUCTORY REMARKS

Collisions with ships are one of the main modern threats to whale survival (Davidson et al., 2012; Ritter and Panigada, 2019). Each collision event is likely to remove – kill – the concerned individuals from their populations, most of which have already been depleted by commercial whaling (Rocha et al., 2014; Vanderlaan and Taggart, 2007). Whereas some populations are recovering from the commercial whaling era, others are still struggling with relatively new threats such as ship strikes. Solutions do exist to mitigate the whale-ship collision issue (Couvat and Gambaiani, 2013; Silber et al., 2008a). However, despite a steady increase in awareness, the shipping industry often fails to adopt or comply with these solutions, and governments often fail to enforce them (Davies and Brillant, 2019; McKenna et al., 2012). Until recently, the lack of robust data has, for a long time, been blamed for the failure of implementing anti-collision solutions (Mannocci et al., 2018; Peel et al., 2018). Nowadays, new factors are highlighted, such as the lack of solution recognition or the disregard for it by the shipping industry (Silber and Bettridge, 2012). More recently, the absence of a holistic assessment of solutions has been identified as limiting the ability of decision-makers to make recommendations, governments to enact enforcement, or industries willingness to act (Ayyub et al., 2007; Geijer and Jones, 2015; Kirchler et al., 2008; G. K. Silber et al., 2012; Sorby, 2018; Whitney et al., 2016).

In order to contextualize this thesis on whale-ship collisions, the introduction is presented in four sections. Firstly, I will describe the extent that collisions cause in the context of other direct threats to whale survival. Secondly, I will focus on the whale-ship collision dynamics and its current management. Thirdly, I will investigate the integration of the human dimension in the management process. Finally, I will define the objectives, the structure, and the contribution of this interdisciplinary thesis, based on the parameters described in the previous sections.

1. EVOLUTION OF HUMAN-INDUCED DIRECT THREATS TO WHALES

The notion of Human-Induced Mortality emerged in the 1990s to define *"the magnitude of annual removals from a stock due to incidental catch and other directed human causes"* (Wang et al., 1994). In 2016, the International Whaling Commission (IWC)[1] created a sub-committee named *"Non-Deliberate Human-Induced Mortality of Cetaceans"* to deal with bycatch and ship strikes (IWC, 2009). In this thesis, I define Human Induced Mortality (HIM) as all the annual removals from a stock due to human activities. HIM is divided into two categories: direct mortality (HIDM) and indirect mortality (HIIM). HIDM includes all mortalities, which occurred directly after a human-whale interaction. Main HIDM causes are due to fishing ship bycatch (Reeves et al., 2013), collision with ships (Ritter and Panigada, 2019), and whaling (Bailey, 2008). Other occasional threats can also be classified as HIDM, such as unusual pollution events (Struntz et al., 2004), or military acoustic events (D'Amico et al., 2009). It should also be noted that HIDMs can be assimilated to the *"serious injury and mortality"*[2] classification of the U.S. government (Andersen et al., 2008; Federal Register, 2012; Moore et al., 2013). While HIDMs remove individuals directly from the populations, HIIMs are due to threats that impact the population's life parameters (e.g., reproduction, feeding, resting), and consequently whale morbidity. HIIMs threats includes anthropogenic noise (Simmons et al., 2004), physical and chemical pollution (Fossi et al., 2018; Hoydal et al., 2015), prey depletion due to overfishing (Bearzi et al., 2006) and climate change (Gambaiani et al., 2009).

In order to understand the extent of collision threat, this section provides a comprehensive analysis of the evolution of all HIDMs and the role of whale-ship collisions in it. It should be noted, that HIIMs are of course taken into consideration in this thesis, but are not extensively described. For more information on HIIMs, the interested reader may refer to the work of Thomas et al. (2016).

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[1] The IWC was created on December 2nd, 1946 by the International Agreement for the Regulation of Whaling with the aim to ensure proper and effective conservation and development of whale stocks (International Agreement for the Regulation of Whaling, 1946). Since then, the IWC has also worked on non-whaling related subjects.

[2] Serious injury and mortality: death or any injury that presents a greater than 50% chance of death to a marine mammal (Andersen et al., 2008; Federal Register, 2012; Moore et al., 2013).

1.1. THE HARVESTING PHASE (1600-1986)

The whale[3] harvesting industry or – whaling – started back in the 17th century. Local and more rudimentary commercial whaling can nonetheless be traced back to earlier eras (Aguilar, 1986; Clapham, 2016). Whales are exploited for their meat and blubber, which is used to produce oil (Moment, 1957). While commercial whaling initially remained at a constant level, the improvement in ship design in the second half of the 18th century made whaling more efficient and the first depleted populations of whales were observed around 1850 (e.g., North Pacific right whales; Clapham, 2016). By the end of the 19th century, several populations were depleted, such as bowhead, gray, humpback, right, and sperm whales. Some of the fastest whales remained relatively untouched, as ship technology was not evolved enough to hunt them down (Clapham, 2016).

The fast whales were rendered vulnerable due to the modernization of the whaling fleet, for which the two successive world wars were a catalyst. The discovery of new and untouched whale populations, associated with technological breakthroughs during World War I and II, and the low price of fuel led to an unprecedented harvest (Bailey, 2008; Rocha et al., 2014). The 20th century whaling alone, accounted for 2.9 million whales killed worldwide (Rocha et al., 2014).

A first response to depletion of whale populations was the adoption of the Convention for the Regulation of Whaling (CRW) by the League of Nations in 1935. Until then, the whale was considered as an open-access resource, but the Convention marked the first step towards regulation through the promotion of *"scientific research as input to regulation"* (Schneider and Pearce, 2004). In 1946, when the accounted killing reached 1.1 million whales, 15 nations signed the International Convention for the Regulation of Whaling (ICRW)[4], and the IWC was set up (Clapham, 2016; Rocha et al., 2014). However, despite the establishment of catch quotas and diverse rules, whaling was still managed as a fishery, and the Convention advocated for the sustainable development of whaling, and not directly for the preservation of whales (Clapham, 2016; Schneider and Pearce, 2004).

[3] In this thesis, the term *« whale »* refers to large baleen whales (Mysticeti) and the sperm whale. Even though sperm whales do not belong to the baleen whale parvorder, their morphological traits make them vulnerable to similar threats.
[4] The ICRW superseded the International Agreement for the Regulation of Whaling (1937). This new convention was drawn up to address the issues that the CRW was unable to resolve.

An International Observer Scheme was put forward as early as 1955. However it took 17 years for the scheme to be implemented, thanks to a shift in the balance of power within the IWC due to the addition of new members. In the 1970s, new anti-whaling members joined the IWC, which led to the first moratorium proposals. Between 1972 and 1982, almost 30 proposals were studied by the IWC until finally one was accepted in 1982 (Goodman, 2017). The adopted moratorium was applied starting in 1986 (Clapham, 2016). Since then, commercial whaling has been banned.

In spite of this moratorium, certain whaling practices remain to this day. In 1981, aboriginal subsistence whaling was adopted for some communities, and quotas for these hunts were set some years later. Aboriginal subsistence whaling has been highly criticized, especially regarding the definition of *"subsistence"* (Gillespie, 2001). Norway and Iceland also continue to harvest whales under objection or reservation of the moratorium (Gillespie, 2003). These countries set their own catch limits, but share the information with the IWC. Note that Russia and Japan used to hunt under the same regime. Also, Japan used Article VIII – *"for the purpose of scientific research"* – of the Convention, as a loophole, to harvest whales (Clapham, 2016; Gillespie, 2000; Schneider and Pearce, 2004). In 2018, Japan left the ICRW and the IWC, and resumed commercial whaling in their territorial waters (Kojima, 2019).

While the IWC appeared to have regulated commercial whaling, some external factors may have influenced the fate of this industry. Schneider and Pearce (2004) argue that whaling was already decreasing before the moratorium implementation efforts of the IWC. They suggested that the decrease of the whaling industry was due to the *"declining stocks, the rise of substitute products, internationally increasing environmentalism, and rising incomes"*, while the IWC contributed to the decline in whaling by setting quotas to avoid harvesting peaks. This theory lies in the "U" shape of the annual catch curve and advocates for a potential "Whale Kuznets Curve" (Schneider and Pearce, 2004)[5].

1.2. THE COMPETITIVE EXCLUSION PHASE (1800-)

In parallel to the harvesting phase, another kind of threat emerged at the beginning of the 19th century. In this thesis, I refer to this phase as the competitive exclusion phase. Czech, amongst others, supported the theory that the conflict between economic growth and biodiversity

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[5] As Czech (2003) defines it, *"the Environmental Kuznets Curve represents the hypotheses that (1) there is a basic conflict between economic growth and environmental protection, but (2) the basic conflict is resolved when enough economic growth occurs"*. For biodiversity-related subject, these hypotheses have only yet been proven for birds (Czech, 2008).

conservation verifies the competitive exclusion principle (Czech, 2000; Czech et al., 2012). The competitive exclusion principle (Gause's Law) was first defined by Hardin (1960) as an ecological process between two non-interbreeding populations occupying the same niche and geographic territory. If one population multiplies faster than the other, then the other population will be displaced and become extinct. From an economic perspective, the increase in the human population or in per capita consumption of natural resources would lead to a decline in non-human species populations. Hence, Czech et al. (2012) theorized that economic growth leads to a compression of lower trophic levels.

The conflict between whale conservation and the fishing and shipping industries can be perceived as competitive exclusion. The economic growth, and consequently the spatial growth, of these industries generates incidental threats – collateral damage –, such as bycatches or collisions. Hence, there has been a reduction – compression (Fig.1) – in whale populations caused by industrial fishing and shipping, which was intensified in the second half of the 20th century (Clausen and York, 2008).

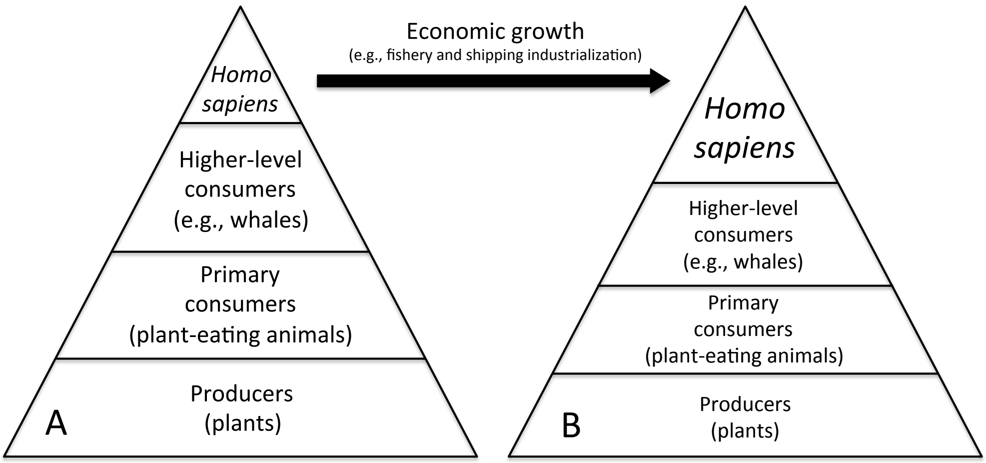

Figure 1. Trophic structure of the economy of nature, with font sizes indicating relative prominence of organisms. The industrialization of fishing and shipping leads to a compression of the higher-level consumers, such as whales. Source: adapted from Czech et al. (2012). Conception: Sèbe

1.2.1. FISHING INDUSTRY (1800-)

The evolution of the fishing industry

Whereas the process of commercial fishing began in the early part of the 19th century, the first significant technological revolution started as late as 1889, with the emergence of steam power ships (Garstang, 1900). New ship designs appeared after the First World War, when ships powered by steam were progressively replaced by diesel engine (Pauly et al., 2002). This switch increased the productivity of fishing of the fleet worldwide, as diesel engines were more efficient than steam (Engelhard, 2008).

Post-World War II marked the dawn of a new era for the fishing industry. The availability of cheap fossil fuel, combined with warfare technology breakthroughs (e.g., radar, echo sounders), dramatically improved fishing power (Zeller and Pauly, 2019). Besides, the spatial expansion of the fishing industry, associated with the Cold War's territorial tensions, accelerated discussions between countries to define an Exclusive Economic Zone (EEZ; Finley, 2016). The resulting Law of the Sea[6], signed in 1982, provided a framework for fishery governance (Zeller and Pauly, 2019)[7].

Between the end of World War II and 1982 (Law of the Sea), a change of paradigm regarding fish management took place. At first, the reduction of fish stocks was believed to increase growth rate and to allow humans to safely harvest the *"surplus"* of fish created by this process (Finley, 2016; Smith, 1995). On this assumption, production was allowed to increase through management rules such as the Maximum Sustained Yield (MSY; Finley, 2016). Between the 1950s and 1960s, the trend in the number of catches was higher than the human population growth (Pauly et al., 2002). Fish stock depletion was first observed in the 1970's. As a result, coupled with the revision of previous MSY models, fish stocks were no longer considered to be able to sustain high harvest rates (Finley, 2016).

In the 1980s, fish stocks decreased even more, resulting in the first set of moratoriums which were put in place in the 1990s (e.g., Atlantic cod; Finley, 2016; Pauly et al., 2002). These initiatives were also supported by the 1995 UN Fish Stock Agreement and the 1995 FAO Code of Conduct (FAO, 2005). Globally, the post-war number of catches increased from 19.3 million tons (1950) to more than 154 million tons (2012; Lewison et al., 2014). Despite fishery management efforts, approximately 63% of the world's fish stock is classified as overfished or collapsed (Lewison et al., 2014; Worm et al., 2009), and the fishing power exceeds by 250% what would be needed to fish at sustainable levels (von Moltke, 2010 in Finley, 2016).

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[6] The Law of the Sea is an international agreement under the United Nations, which defines the rights and responsibilities of nations with respect to their use of the world's oceans. The process started in 1956 (United Nations Conference on the Law of Sea; UNCLOS I) and lasted until 1982 and the signature of the agreement (UNCLOS III) (Finley, 2016).

[7] Before the Law of the Sea, human activities at sea was under the *"freedom of the seas"* doctrine (Ehlers, 2016).

The fishing industry and the evolution of threats to whales

The development of the fishing industry also impacts other trophic levels through prey depletion (HIIM; McCauley et al., 2015), and incidental capture in fishing gear – bycatches (HIDM; Lewison et al., 2014). Aside from non-targeted fish species, the most impacted species by bycatches are in order: sea turtles, marine mammals, and birds (Lewison et al., 2014).

Since the 1970s, bycatches of marine mammals is recognized as a limiting factor for the survival of populations (Reeves et al., 2013). While dolphins – or morphologically similar species – represent a large part of the observed bycatch, this threat has been identified as one of the primary causes of whale mortality (through entanglements). Furthermore, in some cases, whale bycatch removal can be critical, as some populations are low in number, and the removal of a few individuals may have a direct impact at the population-level (Angliss et al., 2002; Thomas et al., 2016; Williams et al., 2009). Entanglements of these large cetaceans in gillnet and trap/pot/fish aggregating devices are the main interactions with fisheries. Large-mesh shark control nets are also an issue in some places (Thomas et al., 2016).

The IWC first addressed the bycatch issue by organizing the 1990 Symposium and Workshop on the Mortality of Cetaceans in Passive Fishing Nets and Traps (Perrin et al., 1994). From this event, six marine mammal populations were designated as at risk from unsustainable bycatch, and three were designated as of particular concern. The Mediterranean Sea sperm whale population has been included in the latter designation, and despite mitigation efforts, remains, to this day, threatened by bycatch (Box. 1; Pace et al., 2016; Rendell and Frantzis, 2016).

1.2.2. THE SHIPPING INDUSTRY (1800-)[8]

The evolution of the shipping industry

Maritime transportation exhibited tremendous changes in the 19th century as did fishing (Stopford, 2009). Steam replaced sail in less than a century; steam engines were inefficient until the 1850s, but within two decades, technological progress had rendered sail obsolete. Between 1840 and 1887, the rate of increase in sea trade was averaging 4.2% per year. New breakthroughs in engine and hull design, deep-sea cables for communication, contributed to an even higher rate of increase until World War II.

[8] Most of this section is based on *Maritime Economics* from Stopford (2009). If no reference is mentioned in the text, the information is to be found in this textbook.

After World War II, the shipping industry faced a new challenge. Labor costs increased and forced the industry to mechanize its processes. The mechanization permitted smaller crews and led the shipping industry to fully adopt the economies of scale. As defined by Stigler (1958), the economies of scale is *"the theory of the relationship between the scale of use of a properly chosen combination of all productive services and the rate of output of the enterprise"*; in other words, for the shipping industry, the bigger the ship, the smaller the cost (Fig. 2). For example, a 170,000 DWT bulk carrier has 5.7 times the storage capacity of a 30,000 DWT bulk carrier, but costs only 2.1 times more. The non-linear relationship between ship size and the operating and capital costs explains these ratios (e.g., crew number, administration).

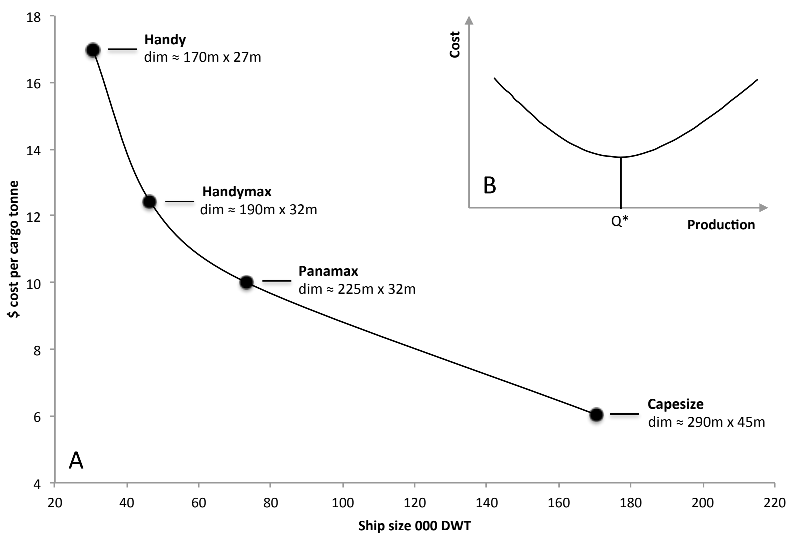


Figure 2. Economies of scale related to ship size for bulk carriers on 11,000-mile round voyage (A) and illustration of the economies of scale theory (B), Q* being the point of perfect economies of scale where the average cost is minimized. Source: modified from Stopford (2009) and McAndrew (2012). Conception: Sèbe.

Besides the mechanization and the increased capacity of ships, the world fleet became more specialized due to changing needs after World War II. Up till then, the world fleet was composed of liner ships – multipurpose ships that could carry various types of merchandise. After the war, it became more specialized according to the merchandise carried (e.g., grain, oil, car, passenger). The post-war reconstruction of cities required a tremendous amount of raw materials, which required bulk carriers. Further, heavy industries bloomed and required fossil fuel to operate, which stimulated the oil tanker fleet. Between 1960 and 1970, the tanker fleet increased by 80% before levelling out after the oil crisis of 1973. Nowadays, the global sea trade is constantly increasing and accounts for more than 90% of global trade (UNCTAD, 2018; Walker et al., 2018).

In 2017, the world merchant fleet was composed of 90,715 ships (Equasis, 2017). The categorization of ships is not straightforward and varies depending on the literature. This thesis will focus on four categories of ship: Bulk carriers, tankers, cargo ships without passengers, and passenger ships. Bulk carriers mainly carry dry merchandise – dry bulk –, but can also carry liquid merchandise. Tankers transport oil and chemicals. Cargo without passengers is defined here as non-human transportation of merchandise that is not carried by bulk carriers or tankers (e.g., cars, containers). Passenger ships include; not only specialized passenger transportation ships, but also Ro-Ro ships, which may carry both human and non-human merchandise (e.g., cars). The four categories described, account for 95.5% of the transportation capacity – expressed in gross tonnage (GT; Fig. 3).

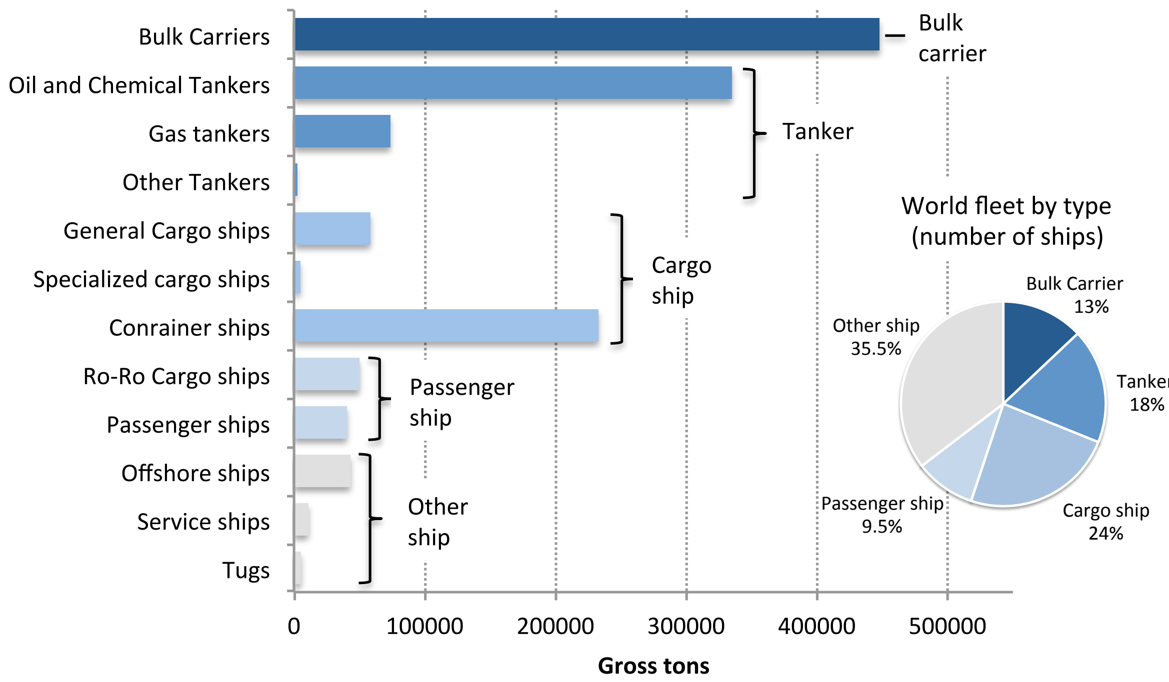


Figure 3. World merchant ship capacity (bar chart) and percentage of the number of ships depending on ship category (pie chart). Data source: Equasis, 2017. Conception: Sèbe (inspiration from Stopford, 2009).

The world shipping trade transported 10.7 billion tons of cargo in 2017 (Fig. 4; UNCTAD, 2018). Shipping provides inter-regional and short-sea transportation, although airborne transportation has increased since the 1960s. Airborne transportation focuses on valuable goods (e.g., electronics, fruit), whereas the maritime trade focuses on goods supporting longer transportation time (e.g., grain, oil). Whereas the airborne trade is growing faster than the shipping trade, the volume of goods transported by ships remains much larger. As previously mentioned, the shipping industry specialized their units to adjust to the diversified merchandise.

Apart from passenger transportation, energy (44%), metal industry (18%), and agricultural (9.4%) trades are the main components of seaborne transportation. Each specialized trade has its own different and therefore complex process (e.g., safety requirement, delivery delay).

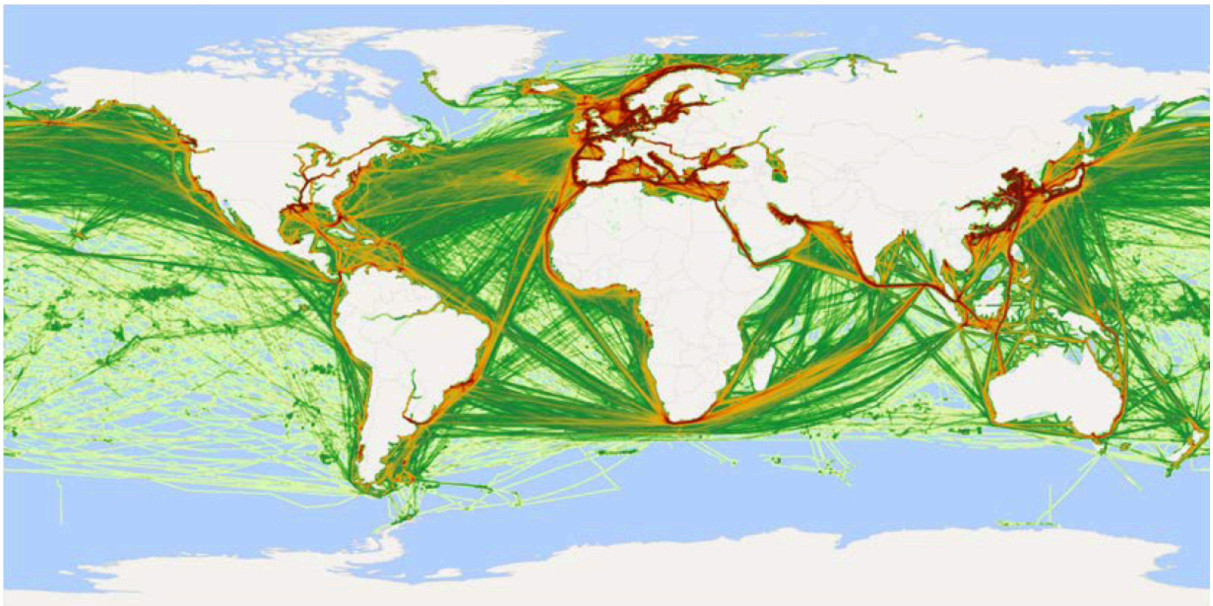


Figure 4. Global traffic density in April 2015, at the spatial resolution of 10-minute longitude by 10-minute latitude Source: Wu et al., (2017).

The shipping industry allows trade on a global basis, but the implementation of international regulations has been slow. Similarly to the fishing industry, the *"freedom of the seas"* doctrine prevailed until the signature of the Law of the Sea (Ehlers, 2016). The United Nations Conference on the Law of Sea meetings set the first rules. UNCLOS I (1958) tackled issues of sea and sea bed ownership, and right of passage by defining the Territorial Sea and Contiguous Zone, the High Seas, and the Continental Shelf. UNCLOS II (1960) aimed at clarifying the unresolved points of the first meeting. Work on the Law of the Sea began in 1973, was adopted in 1982, but only really came into force in 1994. The Law of the Sea provides a "*comprehensive framework for the regulation of all ocean space […] the limits of national jurisdiction over ocean space, access to the seas, navigation, protection and preservation of the marine environment*" (United Nations, 1983 in Stopford, 2009).

A United Nations agency emerged from the United Nations Conference on the Law of Sea (UNCLOS III; 1982): The International Maritime Organization (IMO)[9]. The IMO regulates all aspects of maritime safety and protection of the marine environment for the shipping industry.

[9] Before the IMO, the Inter-Governmental Maritime Consultative Organization prevailed since 1948.

IMO's primary objective is to develop and maintain a comprehensive regulatory framework for shipping (Tarelko, 2012). This organization *"produces conventions which become law when they are enacted by each maritime state"* (Stopford, 2009).

When applying the conventions, particular attention needs to be drawn to the distinction between the flag and coastal states. The flag state makes and enforces laws governing ships registered under its flag, whereas the coastal state enforces maritime laws on ships in its territorial waters (Fig. 5). Hence, a ship will comply with national laws of its flag state regarding its internal functioning (e.g., labor cost), but will abide by the maritime laws of the coastal state territorial waters in which it is navigating. (e.g., speed limits).

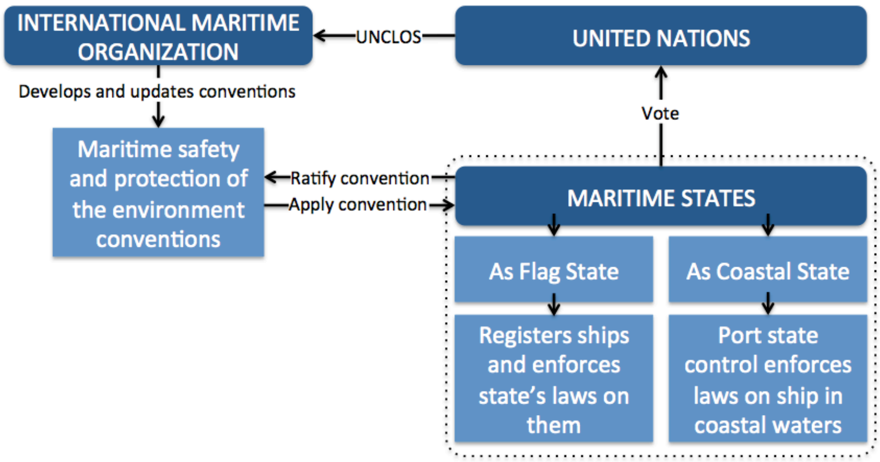


Figure 5. The maritime regulatory system. Conception: Sèbe (simplified from Stopford, 2009).

The shipping industry and the evolution of threats to whales

Similarly, to the fishing industry, the impact of the shipping industry can be perceived as collateral damage – not targeted. The main threats of this industry to whales are the increase in anthropogenic noise (HIIM), and whale-ship collisions (HIDM) (Walker et al., 2018).

Whale-ship collisions lead to direct removals of whales from the populations. While some whales may survive a collision, in most cases, the collision event is lethal (Laist et al., 2001; Moore et al., 2013)[10]. The identification of this threat was initially challenged because of the lack of data. When a commercial ship strikes a whale, in most instances, the crew is unaware of the collision event, as the difference in rigidity between the two objects produces a low impact, which

[10] The whale-ship collision dynamic is described in section 2 of the Introduction.

is not always felt (Gonyo et al., 2019; IMO, 2009; Silber et al., 2010). A dead whale which is the victim of collision may not be noticed, as some carcasses will directly sink to the bottom of the ocean, or drift away from the coast and sink (Williams et al., 2011). Finally, some of the carcasses become stranded on the shore, but might not be identified as a collision victim. The decomposition state or the stranding network[11] organization might impede the course of mortality identification (IWC-ACCOBAMS, 2012). The combination of these factors, which is discussed in Chapter 4, has, for a long time, contributed to the underestimation of the collision threat. Nowadays, improvement in data acquisition has identified collision events to be responsible for a significant proportion of the mortality observed in strandings (e.g., 30%, 35%, 52.1%, and 85% respectively for Hawaiian humpback whales, North Atlantic right whales, Greek Hellenic trench sperm whales, and Hauraki Gulf Bryde's whales; Constantine et al., 2015; Frantzis et al., 2015; Kraus, 2005; Lammers et al., 2013).

Public recognition of this threat began with the North Atlantic right whale case. After a robust assessment of the collision threat, Caswell et al. (1999) indicated that if the collision threat – and the entanglement threat – were not managed, this population would be extinct within less than 200 years. Later, other populations at risk were identified, and large whales were considered the most at-risk marine mammal species, in particular fin whales (*Balaenoptera physalus*), right whales (*Eubalaena glacialis* and *E. australis*), humpback whales (*Megaptera novaeangliae*), sperm whales (*Physeter macrocephalus*), and gray whales (*Eschrichtius robustus*) (Laist et al., 2001; Van Der Hoop et al., 2013). While precise threat assessments are challenging (see Chapter 4), IWC advocated for categorizing collisions as HIDM, and identified the populations most at risk (Cates et al., 2016; IWC, 1999a; Ritter and Panigada, 2019): Western North Atlantic right whale, Eastern North Pacific right whale, Chile-Peru right whale, Arabian Sea humpback whale, Western gray whale; Sri Lanka and Arabian Sea blue whale, Chile blue whale, Mediterranean Sea sperm and fin whale (see Box. 1), Gulf of Mexico Bryde's whale, North-western Madagascar Omura's whale, Canary Islands region sperm whale.

[11] A stranding network is composed of *"regional teams that respond to the stranding of marine mammals and are equipped to collect biological information and samples that can be used to understand the health, population dynamics, and life histories of marine mammals"* (Becker et al., 1994).

1.3. THE CUMULATIVE EFFECT OF HUMAN-INDUCED DIRECT MORTALITY

The level of threats to whales of the whaling, fishing, and shipping industries peaked at different points in time. Prior to the war, whaling was stable, however, the post-war context led to a quick expansion of the industry up till the 1970s. Similarly, fishing expansion started after the Second World War, and peaked in the 1990s. Although, this industry is still growing, it is at a slower rate (FAO, 2016). The expansion of the shipping industry started at the same time but has not yet reached a peak. The shipping industry is highly correlated to the demand for goods (Stopford, 2009). As long as the human population grows and demands the same amount of goods, or higher, the shipping industry will expand within the economies of scale (bigger and faster ships; Baik, 2017).

While peaking at different times, these threats have a cumulative effect on whale populations. Whaling depleted several populations, to the extent that some of were reduced to 1% of the pre-whaling abundance level (Clapham, 2016). Nowadays, some populations are recovering from this era (42%), some remain stable at their post-whaling numbers (28%), while others keep decreasing (10%) or are not assessed (20%) (Clapham, 2016; Magera et al., 2013). The moratorium on whaling marked the end of direct targeted removals – current subsistence or under objection whaling does not represent an *"active"* threat for populations at a global scale (Thomas et al., 2016). Hence, theoretically, the abundance of whales worldwide should have increased relatively rapidly, but has not due to the new emerging threats posed by the fishing and shipping industry – and HIIM.

As illustrated in Figure 6, the post-whaling era should have been characterized by a steeper increase in the number of whales. Unfortunately, the cumulative effect of the fishing and shipping industries – along with HIIM – outweighed the potential for this recovery. The expansion of the fishing and shipping industries started at a time where whale populations were depleted. The growth of these industries therefore did not account for the opportunity offered by the whaling moratorium for a long-time recovery of the whale populations. The presence of more whales inevitably led to an increased probability of human-whale conflict, which probably limited the post-whaling recovery of whales (economic compression; Czech et al., 2012). Moreover, the increase in these populations can be perceived as a hindrance for the fishing and shipping industries, due to the costs incurred (damages or management; Chapters 2 and 5).

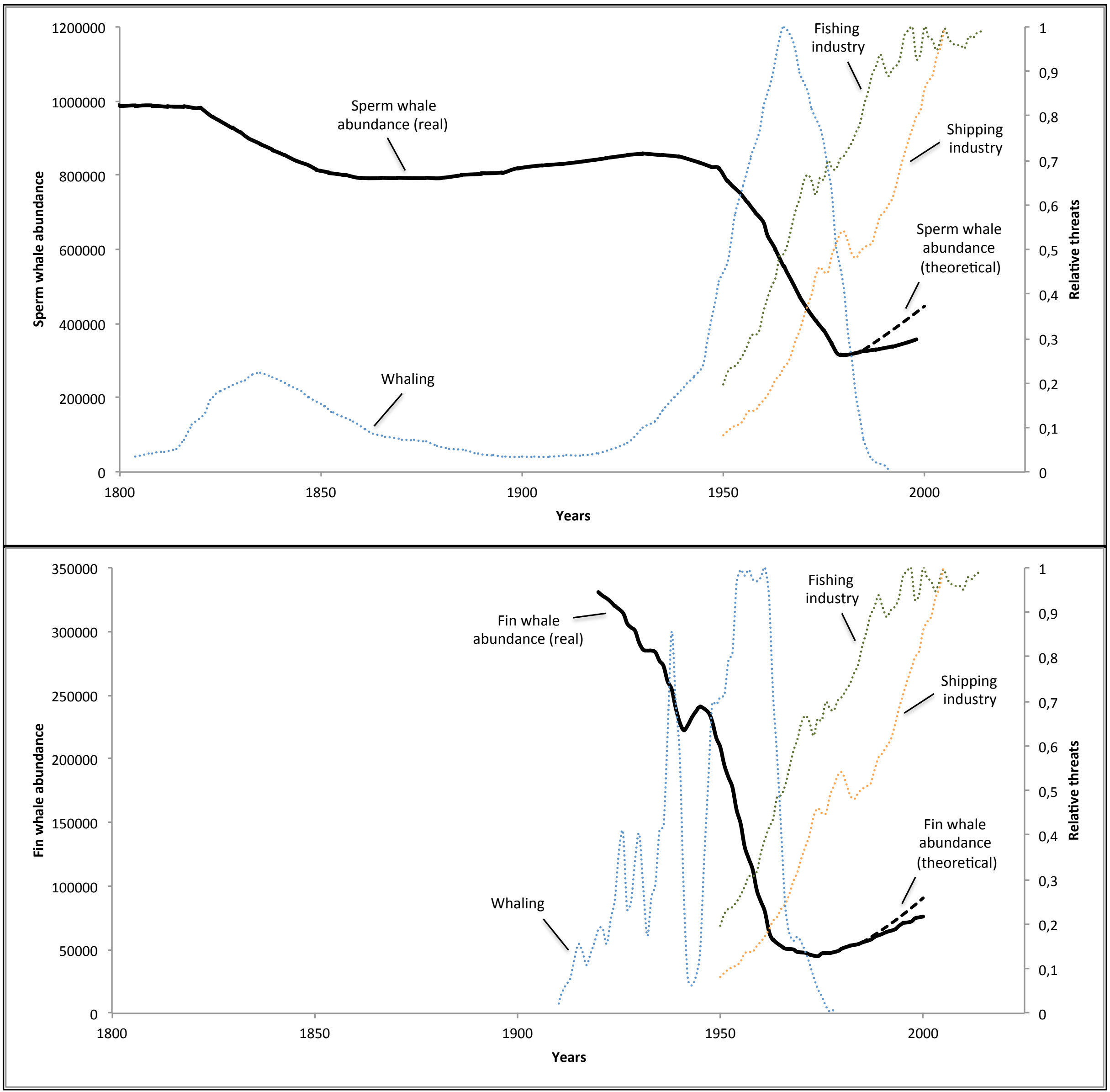


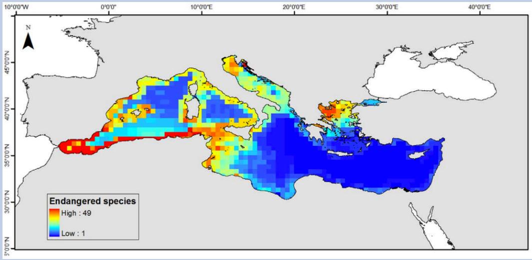
Figure 6. Evolution of the worldwide sperm (top) and fin (bottom) whale populations and the main human-induced direct mortality threats. The threats are expressed in relative value based on the following indicators: the number of catch worldwide for the *"whaling"* threat; the tonnes of capture worldwide for the *"fishing industry"* threat; and the tonnes of cargo transported for the *"shipping industry"*. Theoretical abundances were calculated using a population dynamic model with pre-disturbance parameters (Chapter 4). Data source: FAO, 2016; IUCN, 2018; Schneider and Pearce, 2004; Stopford, 2009; Whitehead, 2002. Conception: Sèbe.

Box. 1: Thesis case study

In order to illustrate the findings of this thesis, the Mediterranean sperm and fin whales' sub-populations were selected as a case study. These two sub-populations are recognized to be threatened by ship strikes (Cates et al., 2016; Notarbartolo di Sciara et al., 2012; Panigada and di Sciara, 2012). This box provides basic information on the case study.

The Mediterranean Sea

The Mediterranean Sea is a semi-enclosed basin of 2,500,000 km². The enclosed characteristic of this sea tends to exacerbate threats to the environment and biodiversity (e.g., plastic and chemical pollution; Coll et al., 2010; UNEP, 2015). The aggregation of threats impacts the health of the two main large whale populations: the sperm and fin whales. Experts raise special concern for the shipping-related threats as the Mediterranean sees 13% of the world sea trade on only 0.8% of the global ocean surface (Equasis, 2017; IWC-ACCOBAMS, 2012).



Box-Figure 1. Biodiversity hot spots for Mediterranean vertebrate species of special conservation concern. Source: Coll et al. (2010)

The Mediterranean Sperm Whale Population

Scientific name: *Physeter macrocephalus*
Abundance: ca. 1,842 individuals (Lewis et al., 2018)
IUCN regional status: Endangered (EN C2a(ii); IUCN, 2012)

The IUCN assessment stipulates that *"the Mediterranean subpopulation is subject to a number of threats that can result in direct mortality. These include bycatches in fishing gear (especially drift gillnets, still extensively used in the central and eastern Mediterranean, whether legally or illegally) and ship strikes. In addition, the subpopulation may be affected by disturbance, particularly related to intense maritime traffic. It is suspected that a combination of these factors has led to a decline (of unknown magnitude) over the last half-century and it is inferred that, in the absence of effective management to mitigate the ongoing threats, the population decline is continuing"* (Notarbartolo di Sciara et al., 2012).

Box-Figure 2. Fin whale. © Reinhard Dirscherl

The Mediterranean Fin Whale Population

Scientific name: *Balaenoptera physalus*
Abundance: ca. 2,500 individuals (Laran et al., 2017)
IUCN regional status: Vulnerable (VU C2a(ii); IUCN, 2012)

The IUCN assessment stipulates that *"Human-induced mortality from vessel collisions and bycatch in fishing gear (Panigada et al. 2006), together with the potential effects of the disturbance caused by growing whale watching activities, lead to the inference that the subpopulation is declining. fin whales have been described as particularly abundant during the summer months in the Corso-Ligurian-Basin, which is considered their major feeding ground in the Mediterranean Sea. A sharp decrease in fin whale abundance has been observed in the Pelagos Sanctuary over the last decade […] While the sharp decrease of fin whales in the Pelagos Sanctuary may be due to whales relocating elsewhere within the Mediterranean, their decrease in prime fin whale habitat must be addressed with precaution, and a population decline in the Mediterranean cannot be discounted at this time"* (Panigada and di Sciara, 2012).

Box-Figure 3. Fin whale. © Adriana Basques

2. WHALE-SHIP COLLISION

While the previous section defined the overall level of HIDM threats endured by whales, this section will focus on the whale-ship collision risk and its management.

2.1. WHALE-SHIP COLLISION RISK

As defined in the risk management nomenclature (ERI/ESA, 2000), the whale-ship lethal collision risk may be expressed as follows:

$$R = F \times S \qquad (1)$$

Where R is the risk of lethal collision, F is the frequency that a collision event may occur, and S is the severity of the consequences of the collision. From a whale conservation perspective, and by simplifying Vanderlaan et al., (2008) approach, we hereby define the risk of lethal collision as:

$$R = P(Collision) \times P(Lethal \mid Collision) \qquad (2)$$

Where *P(Collision)* is the probability of collision between a whale and a ship, and *P(Lethal|Collision)* is the probability of a whale lethal injury after a collision.

2.1.1. FREQUENCY OF A COLLISION

The definition of the frequency of collision is debated in the literature. Theoretically, the overlap between maritime roads and high-density whale areas creates the probability – frequency – of collisions (encounter rate theory; Campana et al., 2015; Redfern et al., 2019; Ritter and Panigada, 2019).

Some authors argue that this overlap creates the probability of encounter, and that the probability of collision is dependent on the ability of the whale and the ship to avoid the collision (Martin et al., 2015; Rockwood et al., 2017). However, the avoidance ability of whales and ships is subject to uncertainty (Conn and Silber, 2013). On one hand, the whales' reaction to oncoming ships is unclear (Lima et al., 2015; Szesciorka et al., 2019), as studies using sound stimulus or acoustic tags showed no – or little – response of whales to approaching ships (McKenna et al., 2015; Nowacek et al., 2007; Szesciorka et al., 2019). On the other hand, the crew avoidance ability is dependent on various limiting factors (Williams et al., 2016), which are studied in Chapter 1. Hence, some authors assume that avoidance is too uncertain to differentiate encounter and collision in model equations (Conn and Silber, 2013; Vanderlaan et al., 2008a), and then define the collision risk as to the co-occurrence between whale and ships (encounter;

Redfern et al., 2019). In this thesis, to simplify, I assume that the overlap between maritime roads and high-density whale areas creates the probability of collisions when discussing the probability, while not forgetting the encounter/avoidance issue.

The difference between the ship, crew, and whale spatial environment is a significant factor of whale-ship interactions, and, therefore, of the frequency of the event (Fig. 7)[12]. The whale-ship collision dynamics are complex. The ship crew operates in a two-dimensional (2D) plane[13] and can encounter a whale as and when an individual surfaces. The whale inhabits a three-dimensional (3D) space and only *"interacts"* with the crew when surfacing. However, while the ship navigates on a 2D plane, a part of the ship operates in the 3D space of the whale; the ship draught[14] can reach up to 25 meters depth depending on the ship size and category (MAN Diesel & Turbo, 2017a, 2017b, 2010), which correspond to areas where some populations spend a considerable amount of time (e.g., the Bryde's whales in the Hauraki Gulf spend 91% of their time between 0 and 14m). Consequently, the crew only detects surfacing whales, depending on various factors (Williams et al., 2016), but not the whales that are within draught reach. This difference in spatial environments need to be taken into account when discussing the collision frequency, and may well impact collision management solutions.

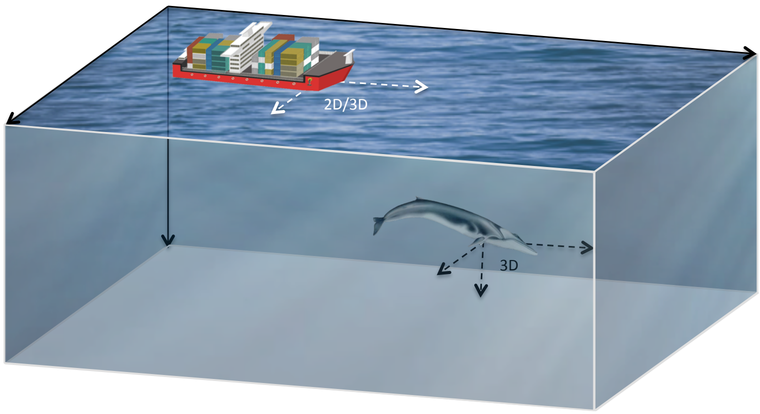


Figure 7. Difference in ship, crew, and whale spatial environment. Whales inhabit a 3D environment, which crosses with the 2D/3D environment of the ships, when coming between the sea surface and the maximal draught depth. The whales' environment only crosses the 2D environment of the crew when surfacing. Credit for whale's pictogram: Maëly Maruzzi / Agence des Aires Marines Protégées. Conception: Sèbe and Guillou.

[12] These aspects are subject to a short communication in preparation (Annex 3).
[13] While using various equipment to navigate (e.g., sonar), none – or almost none – equipment is adapted to detect whales underwater (Silber et al., 2008a).
[14] The draught is the vertical distance between the waterline and the bottom of the hull. It is the submerged part of the ship.

2.1.2. SEVERITY OF A COLLISION

The severity of a collision is in most instances, significant for the whale involved. Laist et al. (2001) defined two kinds of injury. First, the injuries caused by a massive blunt impact, which could lead to fractures of heavy bones, including the skull, jaw, or vertebrae. Second, the injuries caused by propeller impact, which could lead to deep slashes or cuts in the blubber. In addition, Knowlton and Kraus (2001) highlighted haemorrhages and hematomas after a collision. Laist et al. (2001) also categorized the severity of the injury into 5 classes: *"killed (carcass observed); severe (bleeding wounds and/or blood in the water); minor (visible non-bleeding wound, signs of distress, no report of blood); none apparent (re-sighted, no visible wound or distress, animal resumed prestrike activity); and [...] unknown-injury class (animal not observed again and no report of blood)"* (Vanderlaan and Taggart, 2007). This injury classification has been used since 2007 by the IWC to characterize collision events in their ship strike database. The IWC database gathers more than 400 collision events between 1970 and 2010. The IWC is currently updating the database for the 2010-2019 period.

The severity of the impact is highly correlated to ship speed. This relation has been suspected for a long time (Jensen and Silber, 2004; Kraus, 2005; Laist et al., 2001), and was validated with the works of Vanderlaan and Taggart (2007), and Conn and Silber (2013), who used the IWC ship strike database to materialized this relationship (Fig. 8). These authors defined the probability of whale lethal injury depending on the ship speed.

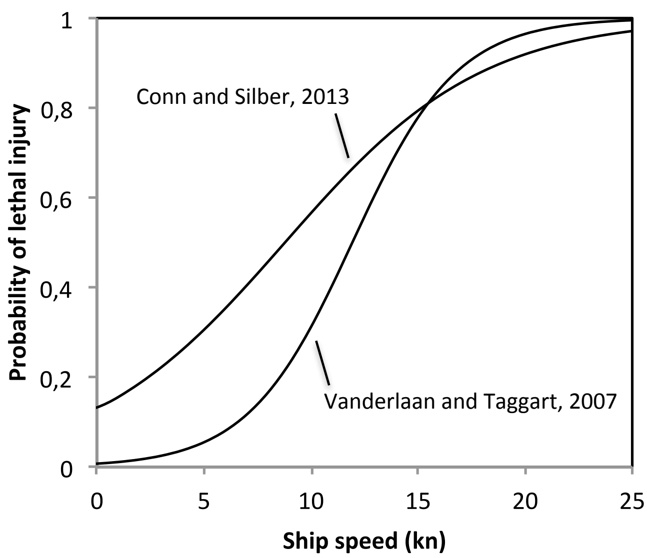


Figure 8. Probability of whale lethal injury after a collision depending on ship speed. Conn and Silber's (2013) study was carried out on an updated IWC database. For more details on Confidence Interval, the interested reader can refer to Vanderlaan and Taggart (2007), and Conn and Silber (2013) works. Conception: Sèbe.

The precise assessment of a collision severity is often challenging, as most studies used the IWC database, which exhibits few data. Some authors try to bypass the need for data by modeling the interaction between ships and whales. Knowlton and his collaborators were the first ones to study the hydrodynamics of the collision events, focusing on possible injuries after a collision and the hydrodynamic behavior of the whale body moments before a collision, under different scenarios (Knowlton et al., 1998, 1995). Silber et al. (2010) studied these impacts more precisely by analysing the level of severity of a whale collision-related injury. These studies confirmed the significance of ship speed, and highlighted some other factors (e.g., propeller diameter, whale orientation). Nonetheless, more research is needed to improve the precision of the present models, and include other naval hydrodynamic models e.g., ship-ship collision, ship-container collision; Zhang, 1999) to improve robustness.

2.2. THE CURRENT STATE OF WHALE-SHIP COLLISION MANAGEMENT

Various conservation schemes exist to protect whales from collisions and other HIM. This section will focus on these schemes, by introducing the global protection framework (e.g., organization, marine protected areas) and the dedicated collision mitigation solutions.

2.2.1. OVERALL PROTECTION OF WHALES

International Union for Conservation of Nature

The scientific community and conservation managers mainly rely on the International Union for Conservation of Nature (IUCN) Red List to specify the level of endangerment of a species (Rodrigues et al., 2006). The International Union for Conservation of Nature is an international association of governmental and non-governmental members, which aims to *"to influence, encourage and assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable"* (IUCN, 2019). The IUCN Red List *"highlights species that are at the greatest risk of extinction and promotes their conservation"* (Rodrigues et al., 2006).

The IUCN global assessments categorize 29% of whales – sperm whale included – as Endangered (n=4), 14% as Vulnerable (n=2), 7% as Near Threatened (n=1), 43% as Least Concern (n=6), and 7% as Data Deficient (n=1) (IUCN database, consulted on 11/06/2019). When the assessments are downscaled to regional scopes, some sub-populations may be categorized otherwise – as in this thesis case study. For more information on IUCN assessments, the interested reader may refer to the IUCN guidelines (IUCN, 2012a).

Despite the extensive use of the IUCN Red List for academic research or conservation, some authors have highlighted certain limits to the IUCN assessments for marine mammals. On one hand, the IUCN assessment of a population is most of the time undertaken by upscaling local research studies to the entire population (see Chapter 4; Reynolds et al., 2009). For marine mammals, their charismatic nature may *"override evidence-based scientific conservation assessments"*, which can lead to inexact assessments (Freeman, 2008). On the other hand, acquiring the required data for assessments on marine species is challenging, which leads to the IUCN categorization of Data Deficient. However, these species may be Data Deficient because, among others, their abundance is low (Parsons, 2016). These species might well be the most threatened.

It should be noted that, the ICUN SSC/WCPA Marine Mammal Protected Areas Task Force developed, the Important Marine Mammal Areas (IMMA). The IMMA aimed to identify *"discrete habitat areas, important for one or more marine mammal species that have the potential to be delineated and managed for conservation"* (IWC, 2019). The integration of whale habitat into Marine Spatial Planning (MSP) is one of the objectives behind the creation of the IMMAs (ICMMPA, 2019).

International Whaling Commission

After the application of the whaling moratorium, the IWC oriented its action towards other threats to whales survival (Wright et al., 2016). The IWC created several committees and sub-committees to manage conservation issues. As mentioned before, marine mammal bycatches were considered in the 1990s (Perrin et al., 1994). After that period, whale watching, chemical pollution, climate change were taken into account by 1995, and more recently, marine noise and marine debris have been studied by the IWC (IWC, 2014, 1999a, 1999b, 1998, 1994).

Whale-ship collisions were first considered as an HIM by the IWC in 1998, and the mortality induced by this threat was accounted for in allowable removals, in the same way as the bycatch threat (Wright et al., 2016). In 2005, the IWC created the Ship Strikes Working Group, which worked on detection and avoidance manoeuvres, repulsion, and crew training (IWC, 2007). In 2009, the IWC received the *observer status*[15] from the IMO, which allows the IWC to contribute to the implementation of mitigation solutions at the IMO level (Wright et al., 2016). Hence, several mitigation measures were negotiated and implemented (see Chapter 1; IMO, 2016, 2012). The

[15] The *observer status* is an agreement of cooperation of the IMO with other intergovernmental organizations on matters of common interest to ensure maximum coordination with respect to such matters.

IWC also coordinates or helps organize several workshops and studies on whale-ship collisions (e.g., IWC-ACCOBAMS, 2012; IWC, 2019).

Treaties, conventions, and agreements

Several treaties, conventions, and agreements protect whales at the regional and international level (Annex 1). Here, I will focus on the main agreement governing our case study (Mediterranean Sea): The Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS). The interested reader can refer to the work of Hoyt (2011) for more information on the other treaties, conventions, and agreements.

In 1996, the ACCOBAMS agreement was adopted under the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention), and became law in 2001 (Notarbartolo di Sciara and Birkun, 2010). The Agreement included *"all the maritime waters of the Black Sea and the Mediterranean and their gulfs and seas, and the internal waters connected to or interconnecting these maritime waters, and of the Atlantic area contiguous to the Mediterranean Sea west of the Straits of Gibraltar"* (ACCOBAMS, 1996). Nowadays, 23 countries are part of the Agreement – 15 in 1996 – which represents 80% of the coastal countries within the ACCOBAMS (Notarbartolo di Sciara and Birkun, 2010).

The ACCOBAMS objective is *"to achieve and maintain a favorable conservation status for cetaceans"* (ACCOBAMS, 1996). To do so, the Agreement implemented measures to address threats to cetaceans by strengthening collaborations between countries within the Agreement (Notarbartolo di Sciara and Birkun, 2010). The ACCOBAMS provides a legal framework to improve knowledge on species status, and their associated threats in the Mediterranean Sea. This improved knowledge triggers actions toward reducing these threats. For example, recently, the ACCOBAMS Survey Initiatives undertook an aerial survey to assess marine mammal abundance, at the same time as gathering information on marine litter (ACCOBAMS, 2018).

Marine Mammal Protected Areas

As defined by the IUCN, a Protected Area is *"a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values"* (IUCN, 2012b). The IUCN defines seven types of Protected

Areas and four types of governance for these areas[16]. While some Protected Areas – according to the IUCN definition – emerged at national levels during the 19th century, the recognition of Protected Areas at the international level started after the creation of the IUCN (1948) and the World Wildlife Fund[17] (WWF; 1961), and the emergence of programmes and conferences, such as the UNESCO Man and the Biosphere Programme, the Ramsar Convention (1971) and the UN Conference on Environment and Development (1972). In 2018, 238,563 Protected Areas were identified (UNEP-WCMC et al., 2018)

While Protected Areas cover 15% of the world's land surface, Marine Protected Areas only cover 7% of the seas (UNEP-WCMC et al., 2018). The IUCN defines Marine Protected Areas (MPA) as *"any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment"* (National Research Council, 2001). Hoyt (2011) accounted for more than 7,000 Marine Protected Areas.

Among these MPAs, 575 incorporate the protection of the cetacean within their objectives (Hoyt, 2011). The International Committee on Marine Mammal Protected Areas (ICMMPA) defines Marine Mammal Protected Areas (MMPA) as *"specially managed protected areas that contribute to the protection of marine mammals and their habitat"* (Notarbartolodi Sciara et al., 2016). While some MMPAs are dedicated to the protection of marine mammals – corresponding to the IUCN category IV (Habitat/Species Management; e.g., Agoa and Pelagos sanctuaries) –, some more *"generalized"* MMPAs include the protection of marine mammals in their management plans, or procure an involuntary – but welcome – protection through the protection of their habitat (Notarbartolodi Sciara et al., 2016). As mentioned before, the governance type of these areas is varied, from MMPAs under the Convention on Migratory Species (CMS), to IUCN Key Biodiversity Areas (IUCN, 2012b; Notarbartolodi Sciara et al., 2016).

While place-based MPAs showed some results (Gormley et al., 2012), in particular, due to their multiplication and their large sizes (e.g., Stellwagen Bank National Marine Sanctuary, Pelagos, and Agoa Sanctuary), the marine mammals' protection is still deficient (Gormley et al., 2012; Hoyt, 2011; Notarbartolodi Sciara et al., 2016). Whales are highly mobile animals, whose dynamics evolve in space and in time, in particular with climate changes (Gambaiani et al., 2009;

[16] An overview of protected areas worldwide can be found at the following website: www.protectedplanet.net

[17] WWF is an international non-governmental organization that mobilizes support for conservation, especially from the general public.

Game et al., 2009; Silber et al., 2017). Consequently, the level of protection provided by MMPA may vary, as in the Pelagos sanctuary case, where the fin whale density hot spot has been identified to cross the boundaries of the sanctuary. The Pelagos sanctuary, therefore, only provides partial protection for this species, which explains that conservation scientists argue to revise this MMPA's boundaries (David et al., 2011). Furthermore, large MPAs and MMPAs lack of monetary or legal means to enforce management measures, and their effectiveness is often debated in the literature (Claudet et al., 2008; Fenberg et al., 2012; Gravestock et al., 2008; Rife et al., 2013)

2.2.2. WHALE-SHIP COLLISION MITIGATION SOLUTIONS

While the previous section described the overall protection of whales, the following section will focus on operational and technical solutions to mitigate the impact of collisions. Operational solutions are related to measures that involve a change in the way ships navigate. Technical solutions are control measures that aim to detect whales better. For more detailed information on these mitigation solutions, please refer to Chapter 1.

Operational solutions

Two primary operational solutions exist when approaching a high probability collision area. First, the speed of the ship can be reduced to lower the severity of an eventual collision. As the ship speed determines the mortality of whales after a collision, this solution reduces the probability of lethal collision. It should be noted that the consequences on the probability of collision are uncertain. On one hand, the reducing speed will increase the time spent in the high probability collision area, which will increase the likelihood of collision (Vanderlaan and Taggart, 2007). On the other hand, reduced speed will allow the crew to detect and avoid a collision more easily, which will in turn decrease the likelihood of collision (Williams et al., 2016).

Second, the avoidance of a high probability collision area is possible to reduce the frequency of collisions. In this case, regularly used solutions are: Area To Be Avoided (ATBA) and Traffic Separation Schemes (TSS). As the name implies, ships are asked to subvert ATBA (IMO, 2007a). Similarly, TSS are designated maritime roads that ships must use to lower the probability of collisions in adjacent areas (Allen, 2014; Fig. 9).

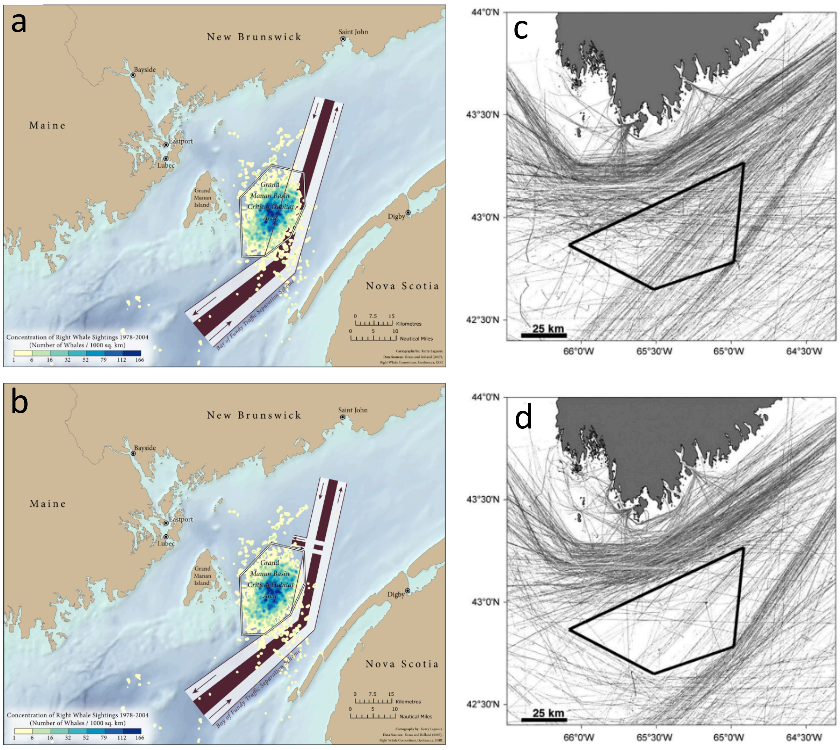


Figure 9. Avoidance operational solutions. Modification of a TSS (a, b), and implementation of an ATBA (c, d). Source: Canadian Whale Institute (2012) and Silber et al. (2012) in Allen (2014)

The applied effectiveness of these solutions depends on several parameters: best-case scenario – theoretical – effectiveness in reducing the risk, stakeholders' compliance, which in turn depends on the overall costs and benefits of implementing the solutions, the regulatory status associated with this implementation (e.g., mandatory or voluntary), and the vigorousness of enforcement (Faure, 2012; Kirchler et al., 2008; Rousseau and Proost, 2005). For more information on the effectiveness of solutions, please refer to Chapter 1.

Technical solutions

Technical solutions 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 (Convertino and Valverde Valverde, 2017; Couvat et al., 2014; Laist et al., 2014; Madon et al., 2017; Silber et al., 2015). Technical solutions can be used with operational solutions in order to provide descriptive information on the area crossed, and, hence, improve the effectiveness of the operational solution (Clark and Peters, 2009; NOAA, 2013; Chapter 1).

Most of the technical tools have either a limited effectiveness, or are too expensive to implement. To this day, the most effective technical solution remains visual detection (Silber et al., 2008b). It is worth noting that progress in Big Data[18] processing and predictive modeling may lead to the emergence of predictive tools in the future (Madon et al., 2017).

3. FROM A BOTTOM-UP TO A TOP-DOWN STANDARDIZED MANAGEMENT OF WHALE-SHIP COLLISIONS

The previous section focused on the description of the whale-ship dynamics, and proposed an overview of the protection and mitigation schemes. This next section will investigate the disciplinary integration of solution proposals, and compare the management of the interaction between whales and ships with other wildlife-vehicle collisions management.

3.1. WHALE-SHIP COLLISION MANAGEMENT: MONODISCIPLINARY, MULTIDISCIPLINARY, INTERDISCIPLINARY, OR TRANSDISCIPLINARY?

The management of environmental issues often requires the added value of various fields of sciences (e.g., Leenhardt et al., 2015; Phillipson and Symes, 2013). While monodisciplinary approaches provide knowledge on a specific issue, the full comprehension of the said issue might only be achieved through interdisciplinary or transdisciplinary approaches (Beder, 2011)[19]. This section investigates the literature on whale-ship collisions to define what is the current approach regarding this issue. It should be emphasized that in this thesis, the disciplinary paradigm of Tress and Fry (2005) is used (see Box. 2).

Several disciplines are required to truly understand the whale-ship collision dynamics and select the best mitigation solution. Knowledge of whale abundance and maritime roads, through

[18] Big data refers to large-growing data sets that include heterogeneous formats: structured, unstructured, and semi-structured data (Oussous et al., 2018).

[19] It is also noteworthy that, the interdisciplinary or multidisciplinary approaches do not guarantee the effectiveness of the management, but simply provide all the required information for the decision-makers (Beder, 2011).

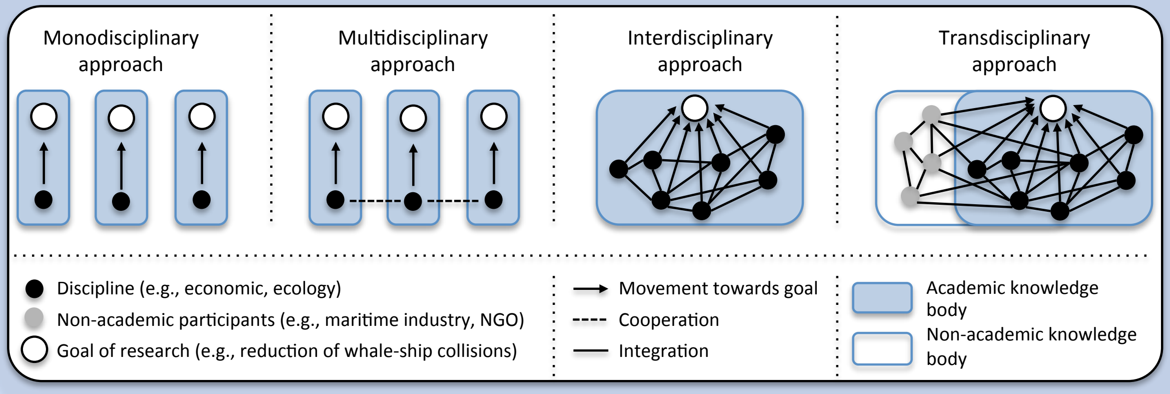
AIS[20] data, is necessary to assess the collision risk. Then, the estimation of the benefit gained when implementing a solution, based on the previously defined collision risk, is required. Plus, as mentioned before, the applied effectiveness of the solution will depend on the stakeholders' compliance, which in turn depends on the legislative status and added costs – and benefits – for the shipping industry.

Through a bibliometric study (see methodology in Annex 2), an analysis of the literature was undertaken on 99 articles and *"grey literature"* to assess the connection between the notions expressed above (Fig. 10). Results show that many studies investigate more or less jointly the collision assessment, the mitigation solutions, and the risk reduction induced. However, the integration of the compliance, the costs, and the legislative status is less apparent.

Hence, in the literature, the processing of the whale-ship collision issue focuses on the assessment and the theoretical effectiveness – and not the applied effectiveness – of a solution (mono- to multidisciplinary approach), without integrating the human dimension (e.g., cost, compliance; inter- to transdisciplinary approach).

Box. 2: Disciplinary paradigm

Tress and Fry (2005) proposed a nomenclature to differentiate monodisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary approaches. Their conceptual framework – slightly modified from their study – is presented in the figure below. This framework is used in this thesis.



Box-Figure 4. Disciplinary paradigm. Conception: Sèbe, adapted from Tress and Fry (2005).

[20] AIS stands for Automatic Identification System, which is a tracking system implemented, in particular, on commercial ships.

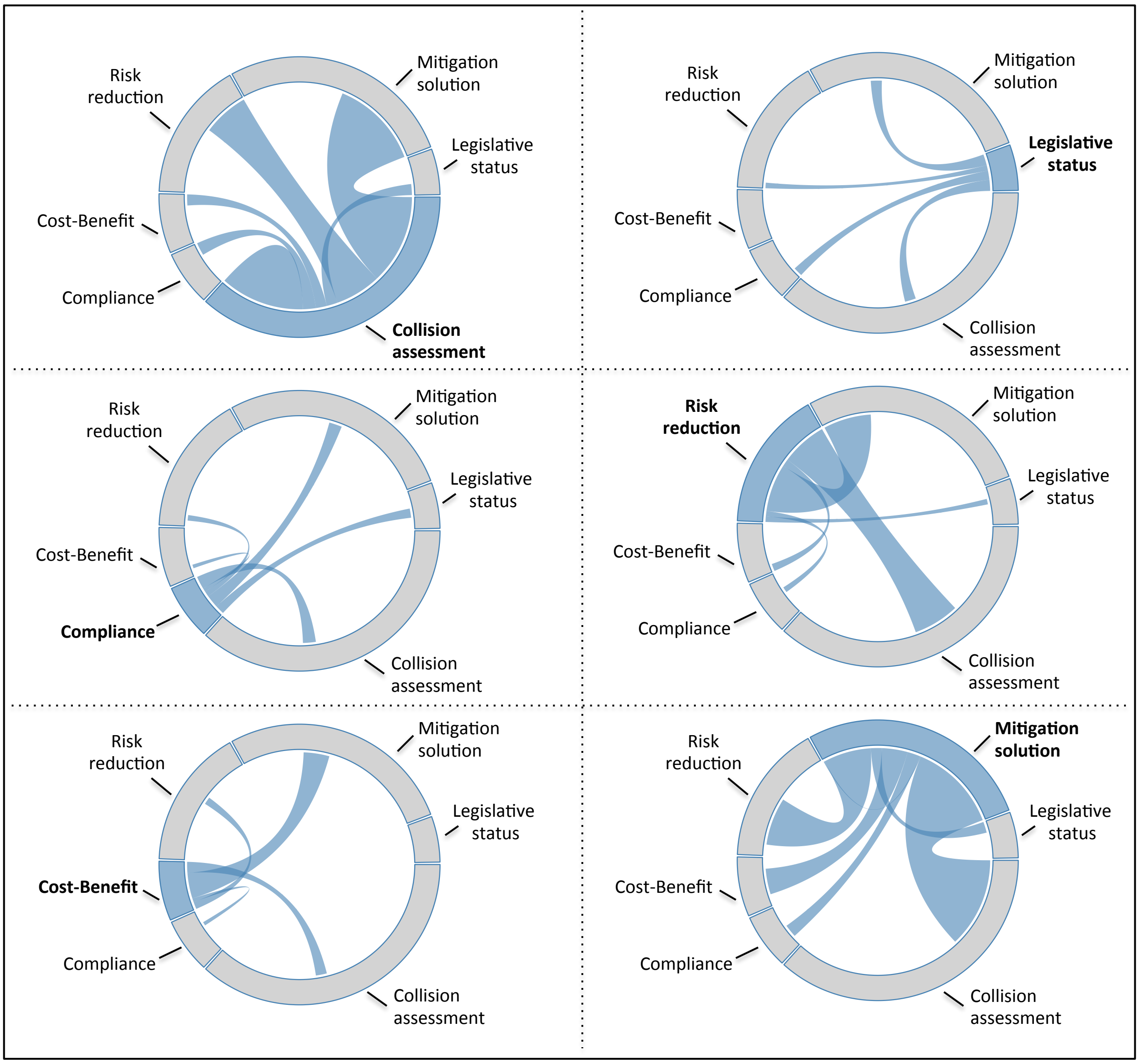


Figure 10. Connection between notions processed in the literature. The size of the semi-circle is proportional to the number of articles processing the related notion. Blue line thickness is proportional to the number of articles processing the notion of origin (in bold) and the notion reached by the blue lines. Conception: Sèbe and Merzereaud.

3.2. LESSONS LEARNED FROM OTHER WILDLIFE-VEHICLE COLLISIONS

The bibliometric study demonstrated that the academic research and management (*"grey literature"*) of whale-ship collisions rests on a mono- or multidisciplinary approach. This section will investigate what is carried out for other types of wildlife-vehicle collision issues. First, the evolution of the integration of various disciplines in the management – with the example of wildlife-car collisions[21] – is investigated. Then, wildlife-vehicle collision dynamics are studied to highlight management perspectives based on collision characteristics.

3.2.1. THE EXAMPLE OF THE MANAGEMENT EVOLUTION OF ROAD COLLISIONS[22]

At the beginning of the 20th century, the development of roads did not account for environmental considerations (Dolan et al., 2006). In the 1960s, these considerations started to emerge within the transport planners' scope with the first proof of pollution, loss of diversity, or urbanisation of rural landscape due to roads. Environmental awareness was the first step towards overcoming the monodisciplinary approach.

The concept of sustainable development emerged through a push of governmental and non-governmental agencies – and the media –, which desired to integrate these new principles into their objectives and decision-making processes. In the following years, the collaboration between different practitioners – such as social scientists, ecologists, or engineers – responded to this demand, and the *"road science"* entered in a multidisciplinary era, and even an interdisciplinary one (e.g., Huijser et al., 2009a). While still in progress, the integration of non-academic perspectives also began with the involvement of the public to assess the willingness to accept or pay for environmental modifications (transdisciplinary approach; e.g., Huijser et al. 2009b). Nowadays, robust environmental assessments before road' construction or modification are required by intergovernmental decision-makers, such as the European Union (EU, 2001, 1985).

To sum up, in the words of Dolan et al. (2006): *"road ecosystem development has evolved to meet the growing needs of society to extend transportation networks, societal concerns and legislative requirements for the prevention of, mitigation of, and compensation for the resultant adverse effects of road ecosystems on the surrounding landscapes"*.

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[21] In this thesis, wildlife-car collisions refer to all road collisions (i.e.., car, bus, truck)

[22] Most of this section is based on reflections from Dolan et al. (2006), adapted to the Tress and Fry (2005) nomenclature. If no reference is mentioned in the text, the information is to be found in Dolan et al. (2006).

3.2.2. WILDLIFE-AIRCRAFT MANAGEMENT: THE MORE APPROPRIATE EXAMPLE FOR WHALE-SHIP COLLISION MANAGEMENT?[23]

Recently, Pirotta et al. (2019) compared the whale-ship collisions to terrestrial road collisions. In their analysis, the authors used a road ecology framework to assess the ecological consequences of shipping for whales, and compared mitigation solutions. This study opened up the reflection towards comparing collisions between whales and ships to other types of wildlife-vehicle collisions. While the terrestrial road collisions analogy shows some promise, the whale-ship collision dynamics might better fit other types of collision. A study of other wildlife-vehicle dynamics is required to highlight the best analogy for the whale-ship collision management (Fig. 11).

Terrestrial collisions (e.g., car, train) are governed by a two-dimensional (2D) plane, where hot spots of collisions are restricted to the roads or railroads (Santos et al., 2017). Unlike other types of collisions, the prediction of cars' movement is challenging, as this transport mode is unplanned (Visintin et al., 2018). While the car avoidance of collisions is possible – but difficult – the avoidance of trains is highly limited due to their high speed and to the impossibility of lateral avoidance (Dorsey et al., 2015).

Wildlife-aircraft collisions are governed by a three-dimensional (3D) space (Walter et al., 2012). Unlike terrestrial collisions, hot spots of collisions are not restricted to a road or railroad section, as airways are not physically materialized. Similarly to trains, aircrafts journeys are planned ahead. The avoidance of collisions is highly challenging for aircrafts, as their high speed prevents accurate visual detection, and adapted avoidance reactions.

As mentioned in section 2.1.1, the whale-ship collision dynamic is complex. When comparing with the other types of collisions, one can observe that collisions between ships and whales bear more similarities with wildlife-aircraft collisions than with terrestrial collisions. In addition to the characteristics described above (3D space, unrestricted hot spot, planned journey, unlikely last-minute avoidance), ships and aircrafts cross international areas and might not be bound to one country regulation during a journey.

[23] These aspects are subject to a short communication in preparation (Annex 3).

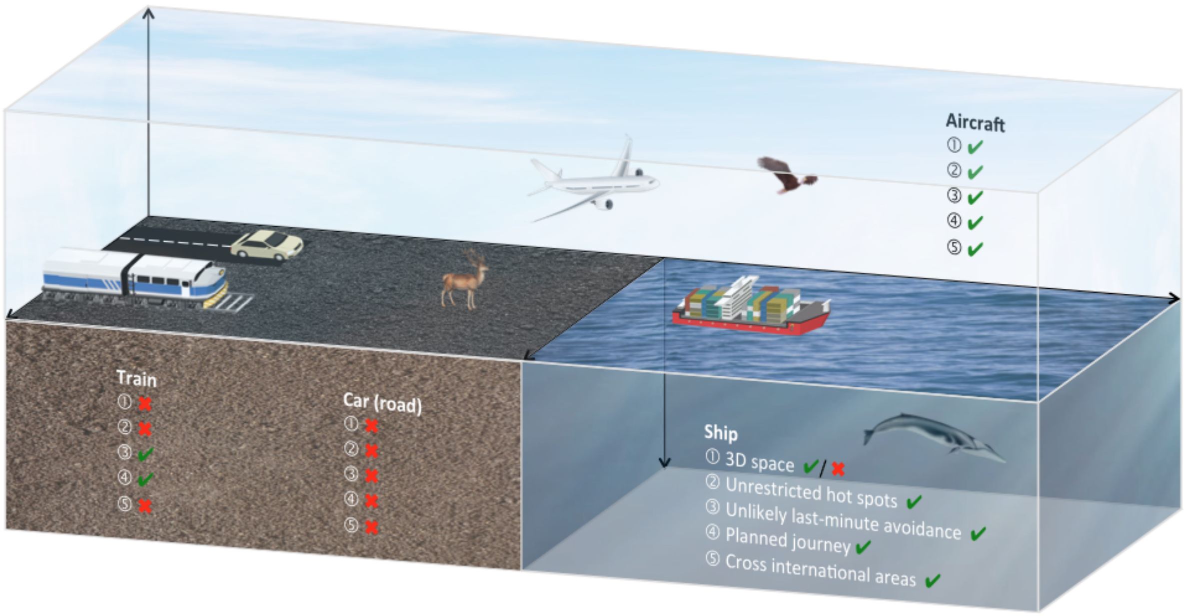

Figure 11. Comparison of the main features of wildlife-vehicle collisions between four transportation sectors. Whale-ship collisions share more characteristics with wildlife-aircraft collisions than with terrestrial wildlife-vehicle collisions. Credit for whale's pictogram: Maëly Maruzzi / Agence des Aires Marines Protégées. Conception: Sèbe and Guillou.

Despite these similarities, the management of these two types of collisions is entirely different. On one hand, wildlife-aircraft collision management follows a top-down process. The International Civil Aviation Organization (ICAO) manages the wildlife-aircraft collisions at the international level since the 1990s. The ICAO is a United Nations Agency *"whose mission is to achieve safe, secure, and sustainable development of civil aviation"*. This agency manages a global strike database, encourages strike reporting, and advocates for risk assessment and cost-effectiveness analysis, through internal standardized processes (ICAO, 2017a). Thanks to the extensive analysis of databases, the wildlife-aircraft collision management is now composed of proactive solutions (e.g., airport selection, seasonal adaptation, compensation; Dolbeer and Wright, 2009).

On the other hand, the management of whale-ship collisions follows a bottom-up process. When a hot spot of collisions is identified, in most cases, solutions are proposed at the regional level with limited risk assessments and no cost-effectiveness analysis. Sometimes, these mitigation solutions are submitted to the International Maritime Organization (Silber et al., 2012), which is the ICAO United Nations agency counterpart. However, these proposals are only accepted if the submitting country member has already implemented the solutions at national level. Otherwise, these proposals are often rejected due to the lack of a holistic approach integrating cost, benefit, and risk reduction induced, which prevent IMO members from making a decision. For more information on these aspects, please refer to Chapter 1.

Motivation is key to the difference in management approaches. The primary concern in aerial collisions was the safety of the crew and passengers. The aviation industry was forced to standardize its processes early in its history, due to fatal accidents resulting from collisions with wildlife (Dolbeer et al., 2015; Kelly and Allan, 2006). However, concerning whale-ship collisions, environmental concerns prevail, as safety and damage to property is deemed low. Consequently, few standardized processes have emerged. Research on safety and damage to property is limited for collisions between whales and ships, but initial estimates may not be as low as suspected in comparison to wildlife-aircraft collisions (ICAO, 2017b; Chapter 2). Further investigation is needed to assess these parameters, as their integration might be crucial for decision-makers (Chapter 1).

As a result of the difference in management processes, proactive solutions are at present restricted to wildlife-aircraft collision management, whereas, in most cases only mitigation solutions are being proposed for whale-ship collisions. As proactive actions are crucial to prevent animal loss (McCauley et al., 2015), whale-ship collision management should follow the course taken by aviation.

4. THESIS OBJECTIVES AND STRUCTURE

4.1. OBJECTIVES

As stated, before, academic research, and the associated management of the collision issue, focus on risk assessment, and on the theoretical effectiveness of mitigation solutions. Economic and logistic dimensions of the shipping industry are often omitted when discussing proposed solutions. Consequently, the compliance of shipping companies is limited, as there is no transparency on the efficiency of solutions. (e.g., Chion et al., 2018; see Chapter 1). Furthermore, the lack of a systemic approach prevents decision-makers from acting despite the various management schemes available (Read, 2008; Sorby, 2018).

So, it is clear that, when comparing the whale-ship collision management to other wildlife-vehicle collision cases – in particular wildlife-aircraft management –, there is a lack of standardized processes. The wildlife-aircraft collision management put into motion by the ICAO seems to be the more suitable to whale-ship collision management. A similar approach might therefore be possible through the IMO in order to promote action. Indeed, while the IWC or local initiatives are essential to manage urgent collision matters – for example critically endangered whale species –, a different approach is required for long-term management of the whale-ship collision issue.

Consequently,, the main question that this thesis will address is:

THESIS QUESTION: How should human and ecological dimensions be integrated into a standard process to improve the management of whale-ship collisions?

To answer this question, two main objectives are set:

1) Define a standardized assessment process for mitigation solutions;

2) Investigate the economic and logistic dimensions needed to achieve a systemic assessment of the whale-ship collision issue.

To achieve the first objective, IMO's processes were investigated to highlight possible similar methodologies to the ones used by ICAO. Chapter 6 of the Wildlife Control and Reduction Manual of the ICAO highlights a process that integrates risk assessment and an overview of costs similar to the IMO's Formal Safety Assessment (FSA) (ICAO, 2012; IMO, 2018a). The 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*" (IMO, 2018a). While mainly used for human and property safety, environmental concerns have recently been studied through the FSA scope over the last two decades (Kontovas and Psaraftis, 2009). In this thesis, I will investigate the suitability of the FSA framework to the whale-ship collision issue.

To achieve the second objective, I will investigate the preferences of the shipping industry, and the social benefit of avoiding whales. While some studies have modeled the economic impact of mitigation solutions, few studies have investigated the willingness of shipping companies, or crews to implement these solutions (e.g., Reimer et al., 2016), depending on maritime traffic logistics (e.g., port call loss). Also, as it will be in Chapter 1, 2 and Chapter 5, the social benefits of whales can be crucial for the FSA implementation, and hence, for whale conservation.

4.2. STRUCTURE

Chapter 1 introduces each step of the FSA. For each step, we describe the original framework (Fig. 12), and the changes needed to use it for the whale-ship collision issue. The following chapters will address the limitations or adaptations highlighted in Chapter 1.

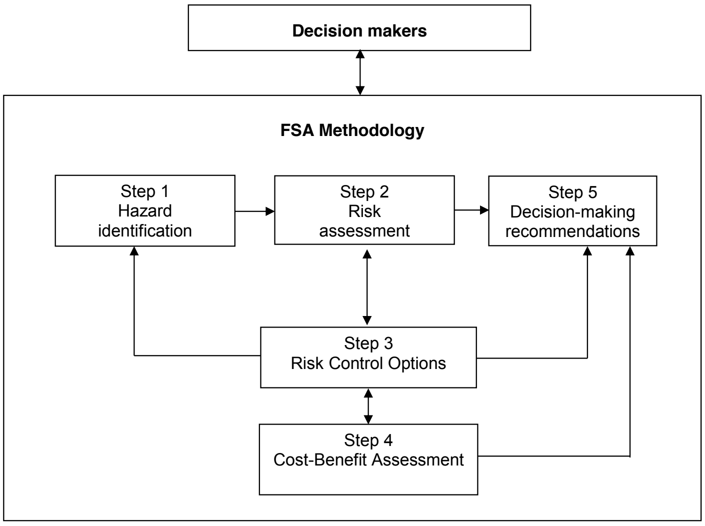

Figure 12. The Formal Safety Assessment framework (IMO, 2018).
Source: IMO, 2018.

Economic aspects are often omitted in whale-ship collision mitigation solution assessment. Chapter 2 therefore proposes a first investigation of the damage cost involved with collisions, which can be considered as avoided cost with mitigation solution implementations (FSA - Step 4). In the Step 4 of the FSA, an assessment of the cost and benefits associated with the mitigation solution is required. However, apart from delay of arrival and additional fuel consumption (Kite-Powell, 2005; Nathan Associates Inc, 2008), other potential costs are not processed in the literature. For example, the cost induced by damage to the ships has not as yet been investigated as it has been deemed low (Van Waerebeek and Leaper, 2008). Chapter 2 proposes a first quantitative approach for estimating the probability of damage as a consequence of whale-ship collisions, and highlights initial cost estimates.

While economic impacts are pivotal to the shipping industry decision-making, logistical aspects should not be underestimated. As mentioned before, research on the economic impact of mitigation solutions is generally done by modeling the implementation of a solution, without accounting for the compliance of the shipping industry (Kite-Powell, 2005; Nathan Associates Inc, 2008). One factor affecting compliance is the logistics of the shipping industry. Before assessing the economic impact, it is crucial to understand how the shipping industry functions. To this end, Chapter 3 investigates the preferences of the ships' crew to two operational solutions when approaching a high probability collision area: speed reduction and avoidance (FSA - Step 3). Using a Choice Experiment method (CE), Chapter 3 highlights the crews' preferences depending on navigational parameters (e.g., length of the journey, type of ship).

In a systemic approach, it is crucial to compare the economic and logistic dimensions with the ecological risk to help decision-making. Chapter 4 examines whale-ship collision risk assessments (FSA - Step 2). In the literature, most of these risk assessments are carried out by modeling the overlap of maritime routes with whale abundance data. However, providing data for the models is challenging. AIS data is expensive, especially for large areas such as the whales' home ranges (Chen et al., 2016). Whale abundance definition requires complicated and costly visual transect by ship or aircraft (Mannocci et al., 2018). By using the unique characteristics of the Mediterranean Sea – our case study –, Chapter 4 proposes a straightforward and inexpensive approach to assess the impact of collisions – and entanglements – on the fin and sperm whale sub-populations, based on stranding data. While less precise than modeling, this approach enables to estimate the severity of HIDM on the Mediterranean whale' sub-populations.

Once the economic and ecological aspects of the whale-ship collision issue are known, decisions on the implementation of solutions can be taken. Chapter 5 tackles a challenging part of the FSA (FSA - Step 4-5). In the Cost-Benefit analysis step of the FSA – which is, in reality, a cost-effectiveness analysis (Kontovas, 2011)–, the trade-off between cost and benefit of a mitigation solution is in favour of the cost. In other words, a solution can be expensive but recommended by the decision-makers. In order to help decision-makers, the FSA guidelines advocate for the use of a risk evaluation criterion. Chapter 5 investigates a way of estimating this criterion for the evaluation of whale-related mitigation solutions through an ecological-economic framework. This Chapter is exploratory and may be continued after the thesis.

CHAPTER 1

A Decision-Making Framework to Reduce the Risk of Collisions between Ships and Whales

"We can't have a rule that applies to a French vessel, and not to an Italian vessel. This is discrimination. We need solutions at the IMO level."

O. Varin, former ferry captain, ICMMPA, 2019

The following chapter has been published in the peer-reviewed journal *Marine Policy:*

Sèbe, M., Kontovas, A.C., Pendleton, L., 2019. A decision-making framework to reduce the risk of collisions between ships and whales. *Marine Policy* 109, 1–12. https://doi.org/10.1016/j.marpol.2019.103697

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 Organisation (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.

Keywords: whale, collision, ship strikes, risk assessment, cost-effectiveness

1. INTRODUCTION

Cetaceans face several threats to survival. Most of these threats are human-induced or amplified by human activities: whaling (Bailey, 2008; Costello et al., 2012; Tinch and Phang, 2009), entanglement (Reeves et al., 2007), ship collisions (IWC-ACCOBAMS, 2012; Reimer et al., 2016), ocean noise (Simmons et al., 2004), pollution (Hoydal et al., 2015), or climate change (Gambaiani et al., 2009). While difficult to quantify, ship collisions are known to be major threats to whales (IWC-ACCOBAMS, 2012; Reimer et al., 2016). 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 (Jacob and Ody, 2016; Silber and Bettridge, 2012). 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 (Vanderlaan and Taggart, 2007). Third, the risk of collision also has increased over the years as a result of increased ship traffic (Stopford, 2010; UNCTAD/RMT, 2012). 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*); Constantine et al., 2015; Fais et al., 2016; Panigada et al., 2006). 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 (Caswell et al., 1999).

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) (Garrison, 2005; Merrick and Cole, 2007; NOAA, 2006; Vanderlaan et al., 2009; Vanderlaan and Taggart, 2009). 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 (Convertino and Valverde Valverde, 2017; Couvat et al., 2014; Laist et al., 2014; Madon et al., 2017; Silber et al., 2015).

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 regulatory status are parameters independently studied when considering the whale collision issue (cf. Annex 2). 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 (Reimer et al., 2016; Silber et al., 2014; World Shipping Council, 2006). To be noted that some successful cases dealing with whale-ship collision have integrated a more holistic approach, leading to higher compliance of the shipping industry (e.g., Panama; IMO, 2016a), even engaging them in voluntary actions (Constantine et al., 2015). The North Atlantic right whales case is a good illustration of the processing of several parameters to achieve a successful interdisciplinary approach (Silber et al., 2015; Tress and Fry, 2005). Constantine et al. (2015) 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 (Cullen-Knox et al., 2017).

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 IMO, 2018a). The use of the FSA for environmental issues is somewhat limited and has mainly focused on oil spills (Haapasaari et al., 2015; Kontovas and Psaraftis, 2008). 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 (Tarelko, 2012). 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 (IMO, 2006a, 2003) or areas to be avoided (IMO, 2017). 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 (IMO, 2018b, 2012a), 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 (IMO, 2016c, 2009, 2008a, 2008b, 2007b). The IMO hardly ever adopts these incomplete recommendations (IMO, 2012a) or only endorses them when the local regulations are pro-active (IMO, 2016a).

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 THE RISK OF 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 to 8 March 2002) (IMO, 2002a). The guidelines have been revised twice since then, the latest revision being in April 2018 (IMO, 2018a).

The FSA was drafted to address the four challenges to which any approach to modern maritime safety regulation must respond. It has to be (Kontovas et al., 2007):

- "*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"*

The IMO envisaged the 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"* (Kontovas et al., 2007). 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 (2005) or Kontovas and Psaraftis (2009).

The FSA framework is composed of 5 steps that integrate all aspects of potential regulations that are relevant to the shipping industry (Fig. 13):

- 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.

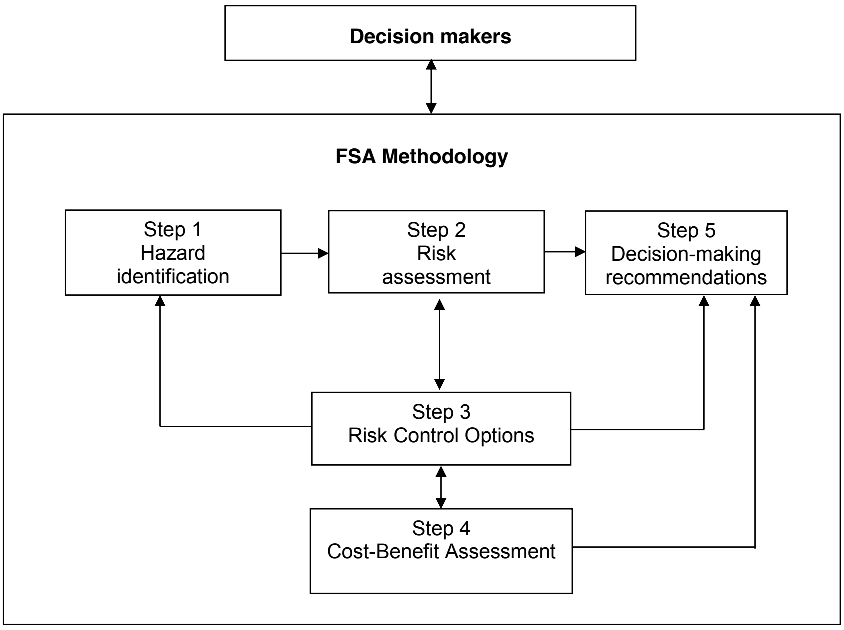

Figure 13. The Formal Safety Assessment framework (IMO, 2018a).

2.2. STEP 1: HAZARD IDENTIFICATION

According to the FSA guidelines (IMO, 2018a), 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. 14). The list of hazards in these sub-categories, which are briefly outlined below, can be found in the Annex 4.

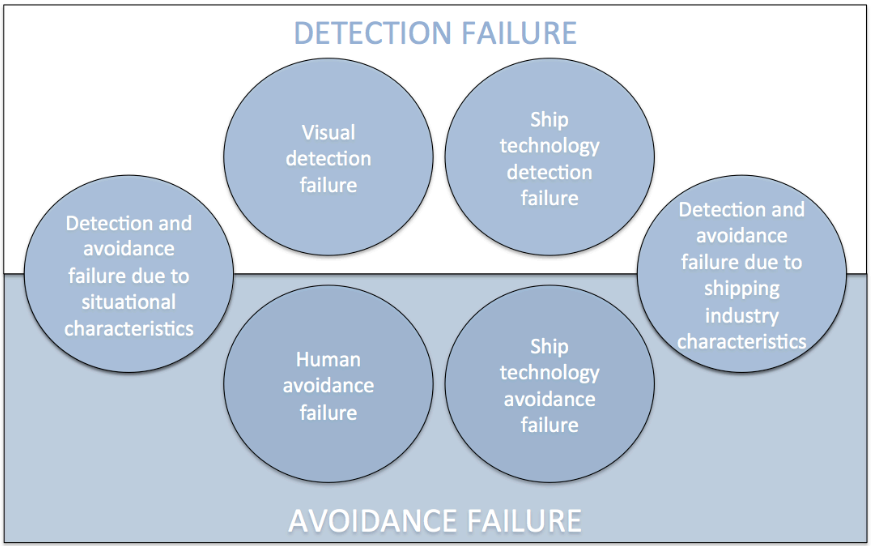

Figure 14. Contributing events categories and sub-categories. Each sub-category includes contributing hazard to collision with whales. Conception: Authors.

- **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; Arcangeli et al., 2012; Couvat and Gambaiani, 2013; Lloyd's Register, 2015; Mayol, 2007; Silber et al., 2008; Silber and Bettridge, 2012; Weinrich et al., 2010). The hazards driven by environmental factors are 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; Williams et al., 2016). Meteorological events also impact the detection of whales (e.g., rain, haze, squall; Arcangeli et al., 2012; Lloyd's Register, 2015; Mayol et al., 2007; Silber et al., 2008; Williams et al., 2016).

- **Human avoidance failure**

The failure of the crew to avoid a whale despite their effort to do so. 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 (Lloyd's Register, 2015).

- **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 (Silber et al., 2008a), the only technology failures here are the ones of 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 these failures are less frequent in the most recent generations of ships (Lloyd's Register, 2015). Other hazards depend on the ship characteristics: turning radius and ship speed (Varin pers.comm.; Silber et al., 2008).

- **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 (e.g., choke points), traffic congestion. Policy factors are linked to TSS and precautionary area, marine safety information, and navigation rules (Convention on the International Regulations for Preventing Collisions at Sea; COLREG; Akten, 2004; Lloyd's Register, 2015; Martins and Maturana, 2013; Ngarajan et al., 2009).

- **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; Kontovas and Psaraftis, 2011; Lloyd's Register, 2015). These hazards are often linked to some marine policies which compel the company to comply (such as the Sulphur Emission Control Areas – SECA or mandatory speed limits; Lloyd's Register, 2015).

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 (IMO, 2018a; Kontovas and Psaraftis, 2009). 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 (Félix and Van Waerebeek, 2005; Jensen and Silber, 2004; Laist et al., 2001; Mayol, 2007; Monnahan et al., 2015; Priyadarshana et al., 2016; Rockwood et al., 2017).

2.3. STEP 2: RISK ANALYSIS

According to the FSA guidelines (IMO, 2018a), 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 (IMO, 2008c, 2004a, 2002b) for which casualty databases are available. 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 (Eleftheria et al., 2016; Psarros et al., 2010). 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 (Jensen and Silber, 2004; Laist et al., 2001). Nevertheless, these 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 (Silber et al., 2008a; Williams et al., 2016). 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 (ACCOBAMS-ECS, 2018; Jensen and Silber, 2004; MacLeod, 2006; Peltier et al., 2019).

An adaptation of the FSA risk analysis is needed to account for the lack of data issue. Over the past decades, whale-ship 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 (Heyning and Dahlheim, 1990; Kraus, 2005; Williams, 2000; Chapter 4). The number of dead whales due to collisions is assessed using this rate (Panigada et al., 2006; Chapter 4). Due to the heterogeneity of the data gathered by the stranding networks (IWC-ACCOBAMS, 2012), 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, and usually, 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 (Peltier and Ridoux, 2015). 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 (Martins et al., 2013). For this approach, the collision risk analysis model of Martins et al., (2013) seems to be the most suited option given its holistic approach. Martins et al., (2013) 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 (Hammond et al., 2017; Laran et al., 2017) or expert judgment density (Notarbartolo di Sciara and Birkun, 2010). 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 (Vanderlaan et al., 2009). Then, the main assumption that ship speed is directly linked to the probability of mortality is integrated into models (Kraus, 2005; Vanderlaan and Taggart, 2007). 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. 15; Martin et al., 2015; Rockwood et al., 2017). 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.

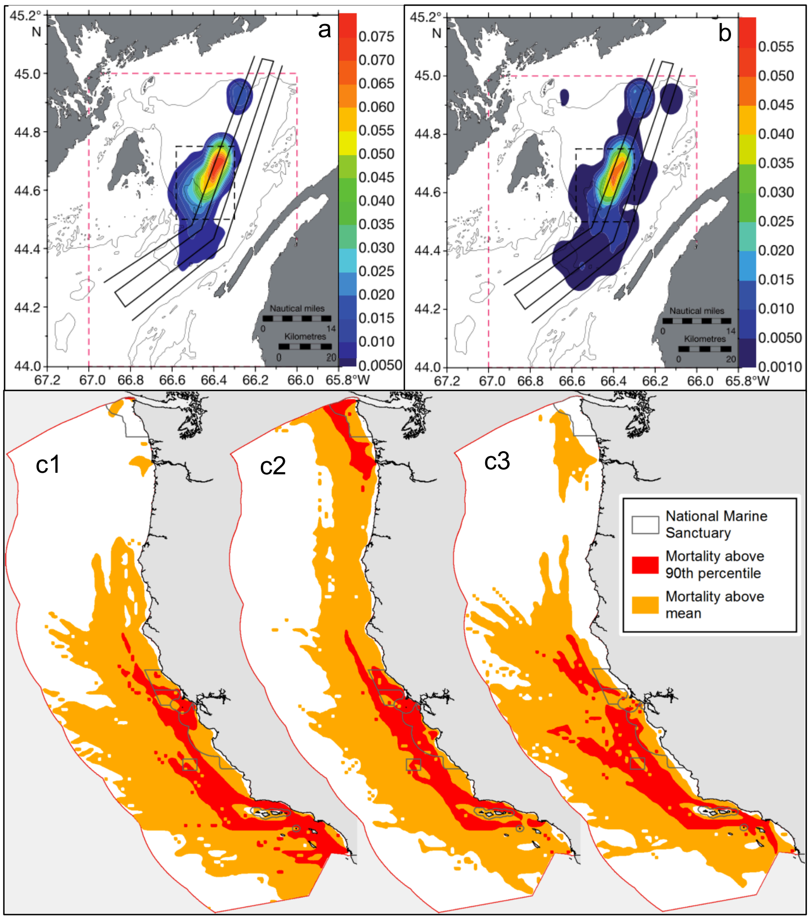

Figure 15. Assessment of the ship-right whale encounter risk (a), the lethal collision risk (b) at small scale (Bay of Fundy, Canada; Vanderlaan et al., 2008a, © Inter-Research 2008) and the lethal blue (c1), humpback (c2) and fin whales (c3) at large scale (US West Coast; Rockwood et al., 2017).

Table 1. Characteristics of existing collision risk assessment approaches.

	Output			Characteristics			
Type of risk assessment	Frequency of collision	Severity of collision	Output example	Price	Precision	Amount of data needed	Primary source
Approach A	Yes	Yes	Number of lethal collisions	Low	Low	Low	Panigada et al., 2006; Chapter 4
Approach B	Yes	No	Collision risk indicators	Medium	Medium	Medium	Martins et al., 2013
Approach C	Yes	No	Probability of collisions	High	High	Medium	David, Di-Meglio and Monestiez, 2018
Approach C	Yes	Yes	Probability of lethal collisions	High	High	High	Vanderlaan et al., 2009

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. The cumulative effect of whale deaths matters. In other words, the death of 10 whales due to collisions might 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 (Boyce, 1992). 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 of the PVA implementation (Kaschner et al., 2012; Mannocci et al., 2018). In those cases, the IMO guideline allows the intervention of experts to define the risk qualitatively, but advocate for a transparent methodology (IMO, 2018a).

In line with the FSA framework, an adaptation of the As Low As Reasonably Practicable (ALARP) concept could be used to incorporate PVA (IMO, 2012b). 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 (Curtis et al., 2015). Figure 16 illustrates a possible adaptation of the ALARP approach, using two LRPs of different level of objective: Critical Reference Point (CRP; IWC, 1996, 1991) and Potential Biological Removal (PBR; Mcdonald et al., 2016; Wade, 1998). Other approaches can be investigated, such as the adaptation of the concept of *"No Net Loss"* (Milner-Gulland et al., 2018).

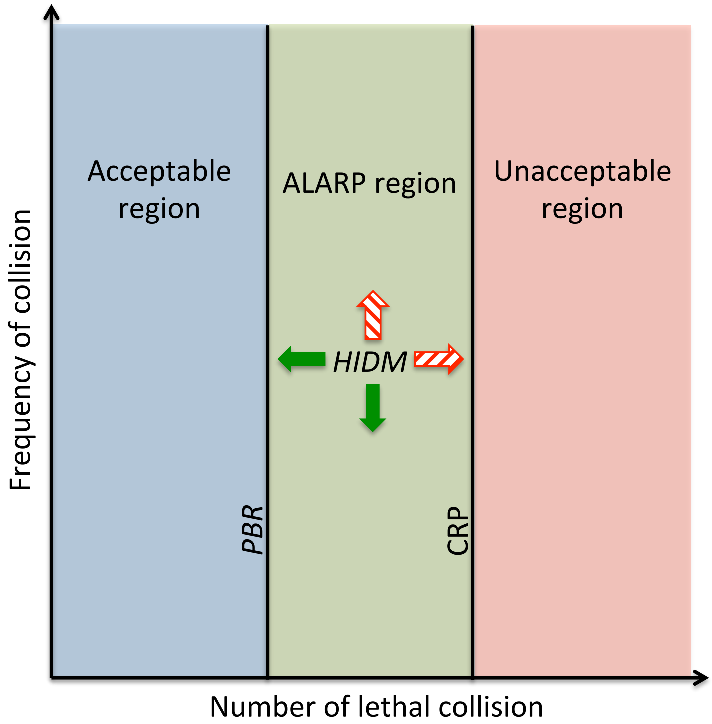

Figure 16. Possible adaptation of the As Low As Reasonably Practicable (ALARP) approach to the whale-ship collision issue, bounded by the Potential Biological Removal (PBR) and the Critical Reference Point (CRP). Green arrows represent positive evolutions of the Human Induced Direct Mortality (HIDM) related to collisions and red striped arrows negative ones. Adapted from IMO, 2012b. Conception: Authors.

2.4. STEP 3: RISK CONTROL OPTIONS

According to the FSA guidelines (IMO, 2018a), 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) (IMO, 2018a; Kontovas, 2005).

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 road systems (see Tab. 2). Technical measures (TRCM) are control measures that aims to better detect whales (see Tab. 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 effective implementation of ORCMs. For example, the Boston passive acoustic network (TRCM-6) is synchronized with ORCM-8 and ORCM-11 (Clark and Peters, 2009; NOAA, 2013).

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	Lagueux et al., 2011
ORCM-2	Speed Reduction (SR)	Fixed	Temporary	Voluntary	Freedman et al., 2017
ORCM-3	Speed Reduction (SR)	Fixed	Fixed	Mandatory	Wiley et al., 2011
ORCM-4	Speed Reduction (SR)	Fixed	Fixed	Voluntary	Constantine et al., 2015
ORCM-5	Speed Reduction (SR)	Dynamic	Dynamic	Voluntary	NOAA, 2013
ORCM-6	Speed Reduction (SR)	Fixed	Dynamic	Mandatory	Welsh, 2018
ORCM-7	Traffic Separation Scheme (TSS)	Fixed	Temporary	Mandatory	National Park Service, 2006
ORCM-8	Traffic Separation Scheme (TSS)	Fixed	Temporary	Voluntary	Garrison, 2006
ORCM-9	Traffic Separation Scheme (TSS)	Fixed	Fixed	Mandatory	Guzman et al., 2013
ORCM-10	Traffic Separation Scheme (TSS)	Fixed	Fixed	Voluntary	Redfern et al., 2013
ORCM-11	SR and TSS	Fixed	Temporary	Voluntary	Ritter and Panigada, 2014
ORCM-12	SR and TSS	Fixed	Fixed	Mandatory	Vanderlaan et al., 2008
ORCM-13	SR and TSS	Fixed	Fixed	Voluntary	Nathan Associates Inc, 2008
ORCM-14	Area To Be Avoided (ATBA)	Fixed	Temporary	Voluntary	Merrick and Cole, 2007
ORCM-15	Area To Be Avoided (ATBA)	Fixed	Fixed	Voluntary	Ritter and Panigada, 2014
ORCM-16	SR and ATBA	Fixed	Temporary	Voluntary	Chion et al., 2018
ORCM-17	SR, TSS, and ATBA	Fixed	Temporary	Voluntary	Chion et al., 2018

Table 3. Technical Risk Control Measures to avoid whale collisions.

Code	TRCM	Examples of implementation	For example
TRCM-1	Right Whale Sighting Advisory System	US waters	Convertino et al., 2017
TRCM-2	REPCET	Pelagos and Agoa Sanctuaries	Couvat et al., 2014
TRCM-3	Whale Alert	US waters	Wiley et al., 2013
TRCM-4	Visual detection (dedicated)	Boston	Weinrich et al., 2010
TRCM-4	Tagging and telemetry	Theoretical	Silber et al., 2008
TRCM-6	Passive acoustics	Boston	Silber et al., 2008
TRCM-7	Ship mounted passive acoustics	France	Lurton, 2013
TRCM-8	Active acoustics	Theoretical	Silber et al., 2008
TRCM-9	Radar	Australia	Anderson and Morris, 2010
TRCM-10	Infrared	Australia	Boebel and Zitterbart, 2015
TRCM-11	Predictive modeling	California (US)	Dransfield et al., 2014
TRCM-12	Sonar	Hawaii (US)	Ellison and Stein, 2001
TRCM-13	US Navy Sound Surveillance System	Washington (US)	Moore et al., 1998
TRCM-14	Acoustic Harassment and Deterrent Devices	Bay of Fundy (Canada)	NMFS, 2004
TRCM-15	Night scope	US waters	NMFS, 2004
TRCM-16	Satellite imagery	Theoretical	Silber et al., 2008

The most critical process in Step 3 is the evaluation of each measure effectiveness 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 Annex 4 and also Nathan Associates Inc, 2012; Silber and Bettridge, 2012). However, some studies have analyzed 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 for high compliance cases (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; Chion et al., 2018; Parrott et al., 2016). 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 et al. (2008).

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	Lagueux et al., 2011
ORCM-1b	SR	Theoretical	100	7.5 - 52	Vanderlaan et al., 2008
ORCM-2	SR	Voluntary	72	35 - 40	Parrott et al., 2016
ORCM-3	SR	Theoretical	100	3.7 – 56.7	Wiley et al., 2011
ORCM-8	TSS	Theoretical	100	10 - 32	Garrison, 2005
ORCM-9	TSS	Theoretical	100	94.8	Guzman et al., 2013
ORCM-10	TSS	Voluntary	96.2	54.3	Lagueux et al., 2011
ORCM-12	SR and TSS	Theoretical	100	69 - 75	Vanderlaan et al., 2008
ORCM-14a	ATBA	Voluntary	71	82	Vanderlaan and Taggart, 2009
ORCM-14b	ATBA	Theoretical	100	39	Vanderlaan et al., 2009
ORCM-16	SR and ATBA	Voluntary	9.3	28 - 34	Chion et al., 2018
ORCM-17	SR, TSS and ATBA	Voluntary	9.7 – 11.2	36 - 40	Chion et al., 2018

The applied effectiveness of the RCO/RCM depends on several parameters: its best-case – theoretical – effectiveness to reduce the risk, and the stakeholders' compliance, which in turn depends on the broad costs and benefits of implementation – i.e., efficiency –, the regulatory status associated with the RCO/RCM (e.g., mandatory or voluntary), and the vigorousness of enforcement (Faure, 2012; Kirchler et al., 2008; Rousseau and Proost, 2005). The applied effectiveness 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 (Guzman et al., 2013; Lagueux et al., 2011; Vanderlaan et al., 2008a). The FSA proposes a framework where all parameters can be processed in an interdisciplinary approach (Tress and Fry, 2005). As the applied effectiveness is difficult to be accurately quantified, the transition from theoretical to applied effectiveness as a measure of outcome is often accomplished by calculating a cost-effectiveness – efficiency – proxy (Kontovas, 2011) that is discussed, among others, in Step 4.

2.5. STEP 4: ASSESSING THE COSTS AND BENEFITS

According to the FSA guidelines (IMO, 2018a), 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:

- "*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 (IMO, 2018a). 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 (Skjong et al., 2005), which defined the criterion of CATS (Cost to Avert one Tonne of Spilled oil) as an environmental criterion equivalent to CAF (Eide et al., 2009). Even though the FSA guidelines only include provisions to assess the environmental damages from oil spills (Kontovas and Psaraftis, 2011), other risk acceptance criterions have been developed and considered for FSA application through recent years (Vanem, 2012). These criterions are mainly focused on air emission, but encourage researches to build relevant criterions for risk assessments, as advocated by the FSA guidelines (IMO, 2018a).

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:

$$NCAWF = \frac{\Delta C - \Delta B}{\Delta R} \qquad (1)$$

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 (IMO, 2018a). For example, a change can appear in whales habitat use or abundance, or even in shipping traffic (e.g., volume, port; Gabriele et al., 2017; Jensen et al., 2015). 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 (Eide et al., 2009);
- The costs of maintenance (Ben-Daya et al., 2009);
- The costs of operation, direct or indirect ones, as the fuel consumption or costs associated with delays in the time of arrival (Nathan Associates Inc, 2012; Silber et al., 2008a);
- The benefits to avoid costs such as the repair costs after a collision or a ship loss (Jensen and Silber, 2004; Laist et al., 2001; Mayol et al., 2007), 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 (IMO, 2006b, 2004b):

- "*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 *"$3m 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 (IMO, 2000; Lind, 1996; UNDP, 1990). 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 (Nathwani et al., 1997). For environmental safety, the second and third approaches are usually used (Kontovas and Psaraftis, 2008; Vanem, 2012). 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) (Eide et al., 2009; SAFEDOR, 2005).

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 (Boxall et al., 2012; Hageman, 1985; Loomis and Larson, 1994; Rudd, 2007; Wallmo and Lew, 2012). These studies are nevertheless costly and time-consuming (Loomis and White, 1996). One way to overcome these constraints is through a benefit transfer study using willingness to pay value from original studies (Lew, 2015; Loomis and Richardson, 2008; U.S. EPA, 2014; Wilson and Hoehn, 2006). 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 (Amuakwa-Mensah, 2018). 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 (Cisneros-Montemayor et al., 2010; O'Connor et al., 2009), the calculation of the lifetime value of a whale can lead to the assessment of the cost of losing a whale (Knowles and Campbell, 2011). Finally, a market approach has emerged recently (Gerber et al., 2014a), although highly discussed (Babcock, 2013; Gerber et al., 2014b; Smith et al., 2014).

As attributing a monetary value to biodiversity is increasingly criticized (Babcock, 2013; Lindhjem and Navrud, 2007; Salles, 2011; Spash and Vatn, 2006), a multi-criteria analysis can also be considered as a new approach to assess the IMO criterion (Da Cunha, 2009). A multi-criteria analysis 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 (Lavery et al., 2014; Robards and Reeves, 2011; Roman et al., 2014). Indeed, these services are most of the time not taken into consideration, as their monetary valuation is often not possible (Luck et al., 2009). Similarly, ecological values can be considered as whales can act as ecosystem engineers or key species of ecosystem functioning (Lavery et al., 2014; Roman et al., 2014). Other dimensions could be integrated, using social indicators (e.g., reputational risk, proactive action; Mather and Fanning, 2019; Silber et al., 2014). An multi-criteria analysis allows different languages of valuation to be used as indicators of each target (Gerber, J.-F., Rodríguez-Labajos, B., Yánez, I., Branco, V., Roman, P., Rosales, L., Johnson, 2012). 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 (Beaumont et al., 2008; Laurila-Pant et al., 2015; Liquete et al., 2013; Pascual et al., 2017). However, the multi-criteria analysis 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. 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 (Couvat et al., 2016; Mayol et al., 2007). 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 (Tucker et al., 2018). In others, the carcass is managed through knackery, explosion or submersion (e.g., in France with a cost between \$28,000 and \$89,000 ($\$US_{2016}$); Couvat et al., 2016; Tucker et al., 2018). For these countries, the second approach may be considered.

To summarise, as per the FSA guidelines, the output from Step 4 comprises 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 (Kontovas, 2005; Chapter 5; Annex 7). 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 – efficient (Kontovas, 2005). 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. 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 the risk 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 (Caswell et al., 1999; IWC-ACCOBAMS, 2012). 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 (Ayyub et al., 2007; Kirchler et al., 2008; G. K. Silber et al., 2012; Silber et al., 2015; Whitney et al., 2016). Recent papers highlighted the potential improvement in collision management that can be offered by the IMO (Geijer and Jones, 2015; G. K. Silber et al., 2012).

Therefore, this paper proposed a holistic approach through a risk assessment framework that has been adopted by the IMO, namely the FSA. The objective of this paper was 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 (Silber et al., 2008a; Williams et al., 2016). 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 (Panigada et al., 2006; Vanderlaan et al., 2009) and its consequence (i.e., the probability of whale mortality), expressed in most cases as a function of the ship speed (Kraus, 2005; Rockwood et al., 2017; Vanderlaan and Taggart, 2007), 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 much research is required in this area. Alternatives such as the *"No Net Loss"* approach could be investigated (Milner-Gulland et al., 2018).

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. 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 (Davies and Brillant, 2019). 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 these options.

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CHAPTER 2

Reducing Whale-Ship Collisions by Better Estimating Damages to Ships

"Ecology is the overall science of which economics is a minor speciality."

G. Hardin, unk

The following chapter has been published in the peer-reviewed journal *Science of the Total Environment:*

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ABSTRACT

Collisions between ships and whales raise environmental, safety, and economic concerns. The management of whale-ship collisions, however, lacks a holistic approach, unlike the management of other types of wildlife-vehicle collisions, which have been more standardized for several years now. In particular, safety and economic factors are routinely omitted in the assessment of proposed mitigation solutions to ship strikes, possibly leading to under-compliance and a lack of acceptance from the stakeholders. In this study, we estimate the probability of ship damage due to a whale-ship collision. While the probability of damage is low, the costs could be important, suggesting that property damages are significant enough to be taken into consideration when assessing solutions. Lessons learned from other types of wildlife-vehicle collisions suggest that the whale-ship collision should be managed as wildlife-aircraft collisions. For several years, the International Civil Aviation Organization (ICAO) manages collisions between aircrafts and wildlife at the international level. We advocate that its United Nations counterpart, namely the International Maritime Organization (IMO), get more involved in the whale-ship collision management. Further research is needed to more precisely quantify the costs incurred to ships from damages caused by whale-ship collisions.

Keywords: whale-ship collision, damage, cost, FSA, wildlife-vehicle collision, risk assessment

1. INTRODUCTION

Collisions between vehicles and wildlife pose significant threats to wildlife conservation, but also to human safety, and economy (Visintin et al., 2018). While less studied than other types of wildlife-vehicle collisions (e.g., car, aircraft, and train), the literature on collisions between commercial ships and whales, also referred to as ship strikes, has increased in the last years. This increased interest is linked to the identification of those collisions as one of the main human-induced threats for whales (IWC-ACCOBAMS, 2012; Panigada et al., 2006; Thomas et al., 2016).

Recent studies have shown that whale-ship collision events occur more frequently than assumed (Frantzis et al., 2019). The ship crew often fails to detect a collision with a whale, as the difference of rigidity between the two objects leads to a low impact force (IMO, 2009; Silber et al., 2010). Hence, most of the time, collisions go unnoticed (Peltier and Ridoux, 2015). Furthermore, as the reporting of these events is rarely mandatory, even noticed collisions might not be reported (Lammers et al., 2013).

Many solutions to avoid those collisions have been proposed over the last two decades (IMO, 2009; Silber et al., 2008a). Nevertheless, most of the time, the implementation of these solutions faces low compliance from the shipping industry (Chion et al., 2017; G. K. Silber et al., 2012). Silber and Bettridge (2012) identified "*lack of public recognition of the rule, disregard for it, or inadequate early enforcement*" as potential limiting factors to compliance. More recently, literature started to highlight the lack of risk and economic assessments of these solutions as an impediment to decision-makers recommendations, government enforcement or industries willingness to act upon the problem (Ayyub et al., 2007; Kirchler et al., 2008; G. K. Silber et al., 2012; Silber et al., 2015; Whitney et al., 2016). As it has been highlighted at the last International Conference on Marine Mammal Protected Areas (ICMMPA 2019), the lack of a holistic vision prevents the implementation of synergies between the environmental and shipping stakeholders; see also Mansouri et al. (2015) and Venus Lun et al. (2015).

Unlike the whale-ship collision case, holistic approaches are implemented for a long time for other types of wildlife-vehicle collisions (Huijser et al., 2009a). The evaluation of wildlife, safety, and economic risks has been used for several decades now to target the most efficient solutions to reduce collisions between wildlife and cars (Seiler et al., 2016), trains (Seiler and Olsson, 2017) or aircrafts (Crain et al., 2015; ICAO, 2012).

In order to promote a similar holistic approach for whale-ship collision management, Sèbe et al. (2019) adopted a framework used by the International Maritime Organization (IMO), namely the Formal Safety Assessment (FSA), to propose a more holistic assessment of costs, benefits, and risks associated with measures to avoid ship strikes. While the probability of collision between whales and ships is addressed in the literature (e.g., Martin et al., 2015), the literature on the economic consequences of a collision is rather scant (e.g., Nathan Associates Inc, 2012). In particular, no extensive research has been undertaken, to our knowledge, to assess the ship damages after a collision with a whale. While this probability has been deemed low (Van Waerebeek and Leaper, 2008), good estimates of both the probability and, actually also, of the monetary consequences from the shipper's perspective are needed to inform a robust assessment of the costs and benefits of proposed mitigation measures, as in the case of other wildlife-vehicle collisions (e.g., Allan, 2000; Conover et al., 1995).

The objective of our study is to evaluate the added value of integrating the ship damages to whale-ship collision management. To this end, we assess (1) the probability of ship damage due to a collision with a whale, using, among others, the International Whaling Commission (IWC) ship-strike database, and (2) provide a brief overview of the potential costs for shipping companies.

2. MATERIALS AND METHODS

2.1. DATA PREPARATION

Since 2007, the IWC collects worldwide ship-strike events information in a public database. The database includes records from 1970 to 2010; data after 2010 is not publicly available. A cross-reference of the IWC database with other databases and scientific publications (e.g., Laist *et al.*, 2001; Jensen and Silber, 2004; Panigada *et al.*, 2006) was performed to check for duplicate entries and gather supplementary information on the recorded events**.** Note that, events including non-commercial ships were excluded (e.g., sailing ships and small boats). Of the 501 entries in the IWC database and additional information gathered, 250 were selected for this study (1970-2019). Hereafter, the selected events will be referred as the Updated Database (UD).

2.2. DAMAGE AND COST INFORMATION

For our analysis, we gathered information on the ship speed, length, and associated damages for the collision events in the UD. In the case where the ship's speed or length was not available in the original dataset, we used online databases such as MarineTraffic and VesselFinder to extract the ship's particulars. As ship speed during a strike is sometimes not provided in the UD, and as ship speed for a given type of ship does not change dramatically over time (1970-2010), when needed, we used average operational speeds based on AIS data for similar ships, as presented in IMO (2014). We believe, though that more information on the exact speed during collisions is needed to get better insights. When the damage status was not available, other sources of information were checked to recover damage information related to the UD, such as IWC archives, IMO Global Integrated Shipping Information System archives, scientific publications, and journal articles. Besides, the type and the cost of damages were included in the UD.

2.3. PROBABILITY AND DAMAGE COSTS

Vanderlaan and Taggart (2007) proposed a methodology to define the *"probability of lethal whale injury based on ship speed"* when struck. The methodology used the IWC ship strike database to derive the probability of lethal injury and has, since then, been widely used as a basis for risk assessment studies (Martin et al., 2015; Nichol et al., 2017). We, therefore, follow the same reasoning to derive the probability of ship damage as a result of a whale-ship collision, depending on ship length and speed. Only events for which information on ship speed, length, and damages were reported are included in the analysis.

The probability of ship damages subsequent to a collision with a whale as a function of the ship speed or length, and their ratio, was calculated by performing a logistic regression analysis, with bootstrapping, using *"R"* (R Development Core Team, 2008). A lack of observations limited the needed degrees of freedom and prevented a logistic regression of both the speed and length variable (Peduzzi et al., 1996). As a result, we used the ratio of the variables as a proxy. Note that the logistic regression is the appropriate regression analysis when the dependent variable, in our case, the damage to the ship, is dichotomous (binary). Bootstrapping is a type of resampling where large numbers of smaller samples of the same size are repeatedly drawn, with replacement, from a single original sample – in our analysis, 1,000 iterations were performed (Haman and Avery, 2019; Venables and Ripley, 2002). To illustrate our results, we then compute the probability of damages on four typical ships, which are often involved in collisions (oil tanker, bulk carrier, container and cargo-ferry ships).

3. RESULTS

3.1. DESCRIPTIVE RESULTS

Most of the events in the UD (N=250) do not include any information on ship damages. Only 16.4% of the events describe the damage status (Fig. 17a). Of this 16.4%, 36.6% exhibit proof of damage, whereas the remaining 63.4% attest to the absence of damage to the ship. Most of the events in the UD do not include information on the area where the ship was struck (58.4%; Fig. 17b). Collisions in the front part of the ship seem to be the most frequent type of collision. 82.8% of these events were most likely noticed because the whales were stuck on the bow. Hence, the proportion of frontal impacts may be an overestimation in comparison to non-frontal impacts. Non-frontal impacts include events that occurred on the ship draught, except the bow section (foredraft).

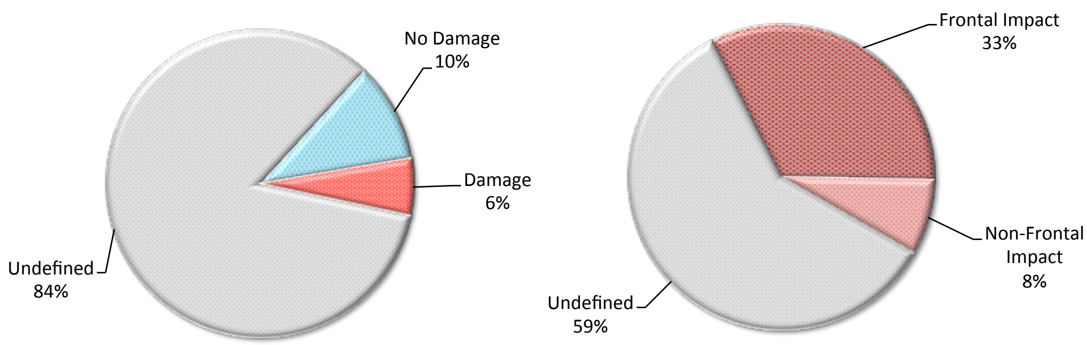

Figure 17. Damage status (left) and area of collisions on ships (right) in the UD in percentages. Conception: Authors.

The primary damages identified were done to the following appendixes:

- Bow (hull);
- Hull;
- Propeller blade;
- Propeller shaft;
- Rudder;
- Steering arm;
- Stabilizer;
- T-foil.

There is very limited information regarding the damage costs in the database, as only 3 records include the costs of damages (1.2% of the UD). First, the replacement of a propeller blade was estimated at $125,000 (US$$_{1991}$). Second, multiple damages to the steering arm and to the hull, which lead to a waterway, of a ship were evaluated at $1,000,000 (US$$_{1991}$). Finally, several damages on a shipping company fleet between 2004 and 2006 led to an overall cost of $3,500,000 (US$$_{2006}$). Some events described speed reduction due to whales stuck on the bow, which may have resulted in additional expenses as a result of increased fuel costs due to the increased time at sea, and to the delayed arrival at ports. Note also that, in total, 2 human losses and 194 human injuries (three events are responsible for this total) are reported in the UD.

3.2. REGRESSION RESULTS

Based on extensive analysis and cross-references with other sources, we were able to obtain the required information for the regression (i.e., joint information on the ships' speed, length, and the damage status subsequent to a whale-ship collision) for 12.8% of the events in the UD. These events were used in the regression analysis.

We performed three separate regressions: one taking only ship speed into account, another with ship length only, and one with the ratio of speed to length; see Table 1 for the results. As the models are estimated through a maximum likelihood method, the Akaike Information Criterion (AIC) can be used to select the best model; in our case the specification with the ratio of speed/length has the best overall performance (i.e., having the lowest AIC; Table 2; Figure 18; DeLeeuw, 1992). A large dataset, of course, would allow for the testing of more specifications. The probability of ship damage can be calculated as: $P_{damage} = \frac{1}{1+e^{-(\alpha+\beta\times\chi)}}$, where α, β, and χ are expressed in Table 5.

Table 5. Logistic regression results.

Logistic regression	α [CI]	β [CI]	χ	P-value	Adjusted R^2	AIC
With speed only	-4.194 [-7.829; -1.753]	0.176 [0.064; 0.347]	Speed	0.0006	0.409	35.55
With length only	0.728 [-0.461; 2.034]	-0.017[-0.034; -0.004]	Length	0.005	0.286	39.52
With a speed/length proxy	-2.377 [-4.053; -1.097]	3.346 [1.485; 5.935]	Speed/Length	$9\text{x}10^{-5}$	0.505	32.08

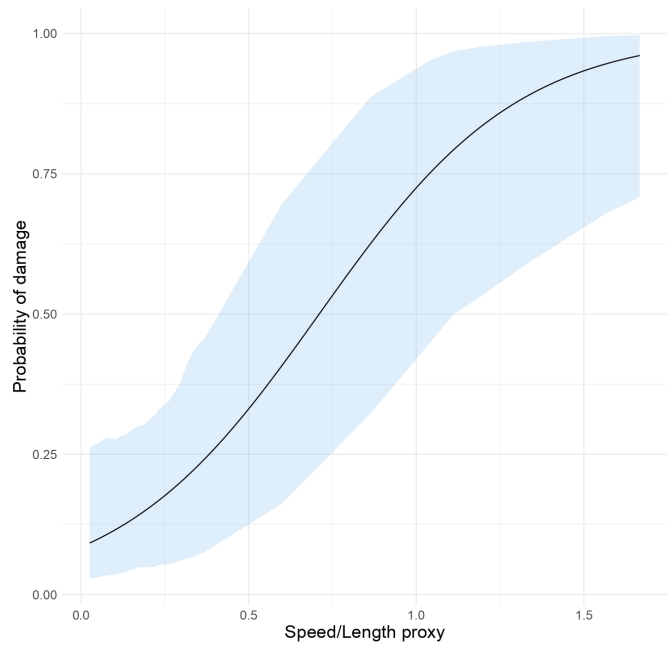

Figure 18. Probability of ship damage depending on a speed/length proxy. The blue area represents the confidence interval. Conception: Authors.

We illustrate our findings using four *"hypothetical"* ship types to show the impacts of ship length and speed on the probability of damage. We use the best model (with the speed/length proxy) to calculate the probability of damage for these typical ships (Table 6). Our study focuses on large commercial ships, as these are the ones that inflict most damages to whales (Ritter and Panigada, 2019). These are also the focus of potential risk and economic assessments of mitigation measures within the International Maritime Organisation (Sèbe et al., 2019).

Table 6. Results of the logistic regression model on the hypothetical ships selected for the study.

Ship category	Oil Tanker	Bulk Carrier	Container ship	Cargo-Ferry
IHS StatCode5v	A13	A21	A33	A34
Ship type	Suezmax oil tanker	Panamax bulk carrier	Container ship	Ro-Ro-pax
Capacity	166,300 DWT	63,580 DWT	5,150 DWT	9,710 DWT
Length overall (Loa)	281.1 m	199.9 m	147.7 m	165.25 m
Selected speed (MarineTraffic)	13.3 kn	13.7 kn	12 kn	18.5 kn
Speed/Length proxy	0.0473	0.0685	0.0815	0.1120
Probability of damage after a whale-ship collision (P_{damage})	0.0981	0.1046	0.1086	0.1190

The logistic regression model results show that the probability of damage for the typical commercial ships is around 0.10 (Table 2). In other words, after a whale-ship collision, there is 1 out of 10 chance that a commercial ship would exhibit some damages. The Cargo-Ferry (A3) category seems to be the most at risk as some of these ships can achieve very high speeds. For example, high-speed passenger ships exhibit the most damages in the UD, as their Speed/Length proxy is high (e.g., Ryu *et al.*, 2010).

4. DISCUSSION

4.1. DESCRIPTIVE RESULTS

The UD includes a limited amount of data in comparison with other wildlife-vehicle collisions datasets. In contrast, the Federal Aviation Administration (FAA) gathered 99,530 collisions events between 1990 and 2014 (vs. 250 for the UD in 40 years; Dolbeer *et al.*, 2015). Nevertheless, some interesting comparisons can be made. Indeed, the percentage of damage status mentioned in the wildlife-aircraft collision reports is between 16% and 45%, and damage costs are mentioned in 5% of the events (Anderson et al., 2015; Dolbeer, 2011). These percentages are higher – or roughly equal for the lower boundary – to the ones presented in the UD (16.4% and 1.2%, respectively). By taking into account that reporting is more standardized for aviation (ICAO, 2017b), we can assume that reporting standardization of whale-ship collisions would lead to an increased percentage of damage information in the UD. Furthermore, while the number of collisions between aircrafts and wildlife is higher than the ones between whales and ships, it is interesting to notice that, in the USA, in 2014, there were 32.52 strikes per 100,000 aircraft movements (Dolbeer et al., 2015). In comparison, from Panigada *et al.*, (2006) and Rendell and Frantzis (2016), we can account for around more than 50 whale collisions per 140,000 ship movements in the Mediterranean Sea, which is equivalent to 35.71 ship strikes per 100,000 ship movements (gross estimation of ship movements based on AIS data from the ENVIGIS software). Of course, further research needs to be performed, but the order of magnitude expressed in this paper advocates for a similar risk, in terms of probability of occurrence.

4.2. PROBABILITY OF SHIP DAMAGE

Our study estimates the probability of ship damage as a result of a whale-ship collision by using a logistic regression model in line with Vanderlaan and Taggart (2007). Similarly to their study, the limitation of data, and the non-integration of relevant variables to shipping (e.g., thickness of the hull, material resistance; Zhang, 1999), or whales (e.g., size, direction) results in large confidence intervals. Nevertheless, our results represent the first step towards the integration of ship damages in whale-ship collision risk assessments.

Results show that Cargo-Ferries (A3) ships face the most significant risk for damage, especially passenger ferries and high-speed passenger ships. The literature revealed several events of severe impacts involving these ship categories. These events lead to a sudden loss of speed, damages requiring towage, or human injuries and fatalities (Laist et al., 2001; Ryu et al., 2010). Other ship categories exhibit lower probabilities of damages. Nevertheless, the overall probability of ship damage for large commercial ships seems to be around $P_{damage} \approx 0.10$, although again, we want to stress out that the dataset is very limited. This observation may indicate that some damages may go unnoticed, or are not linked to a ship-strike, even when the ship requires repairs.

By using a logistic regression model, our study allows a straightforward assessment of the risk reduction induced by a particular collision mitigation solution: speed reduction. When implementing speed reduction, one can observe a reduction in the probability of whale lethal injury (Parrott et al., 2016; Vanderlaan and Taggart, 2007). Based on our study, the probability of damage can also be estimated to expose the risk reduction in ship damages for this mitigation solution. If a Cargo-Ferry of 165 meters length and navigating at a speed of 18.5kn ($P_{damage} = 0.119$) is asked to reduce its speed to 12kn, it reduces the risk of damage by 11% ($P_{damage} = 0.106$). To be noted that at the same time, the probability of lethal injury to whales is reduced by 45% (from 0.937 to 0.507 based on the model derived by Vanderlaan and Taggart, 2007).

Note that this study assesses the probability of damage but does not deal with the severity of the damages, as there are not sufficient data in the IWC database. The severity depends on several factors, such as the thickness of the hull, the material resistance, or the shape of the bow (Liu et al., 2018). Some hydrodynamic models were used to study the behavior of these parameters under different scenarios, i.e., ship-ship, ship-container, and ship-floating log collisions, or groundings (Zhang, 1999). Some researchers studied the hydrodynamics of a whale-ship collision, but in order to assess damages to whales (Knowlton et al., 1998; Silber et al., 2010). To our knowledge, there are no similar studies on ship damages. The undertaking of such studies focusing on the damages to ships after whale-ship collisions would improve our understanding of these events and help improve the management of the risk that ships face as a result of ship strikes. Note that there is a parallel body of literature on dynamic models for wildlife-vehicle collisions (e.g., car and train), which could be applied to whale-ship collisions (Anderson et al., 2015; Visintin et al., 2018).

4.3. COSTS OF DAMAGE

Damage costs to ships can be divided into two categories. One is related to the ship repair cost, which dependents on several factors, such as the extent of the damage, the cost of replacement parts, the place of repair (difference in labor costs and raw materials depending on localization of the repair yard), the docking time required and the workload of the yards (IMO, 2010). The second category is the loss of earnings, as the ship is unable to trade (Stopford, 2009).

Estimating these costs is very challenging as there is a significant variation in costs between ship categories (Stopford, 2009). The costs of damages in the UD are expressed only for 3 records; more observations would obviously result in more accurate assessments of these costs. Nevertheless, the literature allows giving an insight on costs associated with whale-ship collisions. According to the UD, the damages to the hull, and the propeller blades can be extensive. Below, we highlight the estimations of some repair costs related to these damages.

The cost of repair for a breached or warped hull depends on labor costs, the price of steel, and the price of docking. The steel work associated with this repair would require between 60 and 105 man-hours for the hypothetical ships selected in the study (Butler, 2012). The number of docking days associated with these man-hours will depend on the number of workers and the length of shifts. The amount of steel needed would be of between 260 and 470 kg, which would not be expensive as the price of steel is at 711 $/t (worldsteelprices.com, accessed on 09/25/2019). The dry-docking costs for repair differ depending on various factors (Hansen, 2013), but can be estimated at a few thousand dollars per day (Guarin, Konovessis and Vassalos, 2009; IMO, 2010, Piriou company, comm.pers.)

The cost of repair for a damaged propeller blade also depends on labor costs, the price of replacement parts, the price of docking. According to Butler (2012), the work needed to replace the propeller blade can vary between 100 and 240 man-hours for the ships that were studied. The price of parts replacement will depend on various parameters. For instance, the UD described that the replacement of a propeller was estimated at $125,000 (US$$_{1991}$) for a 126m naval ship. Of course, the replacement cost of a propeller will depend on the size and type of the ship, and the value here given is purely indicative of an example of cost. Similarly to hull work, the dry-docking costs can be estimated at a few thousand dollars per day (Guarin, Konovessis and Vassalos, 2009; IMO, 2010, Piriou company, comm.pers.)

Revenue losses are determined based on the time during which the ship has been deprived of income (the loss of time) and the loss of income per day (the daily amount). The income of the ships depends on various parameters, including the type of trade and charter (e.g., if the ship is time-chartered or in the spot market), the ship type and commodity carried, amongst others. The income of ships (even for the same ship, carrying the same commodity on the same route) varies substantially, mainly as a result of the supply of the ships and the demand for transport work (Stopford, 2009). For instance, a bulk carrier (e.g. the one presented in Table 2) chartered for 1 year had an average revenue of around 10,000 US$ per day in 2017 and 13,029 US$ per day in 2018. On the other hand, a very large oil tanker carrying oil from the Arab Gulf to Japan had an average net profit of around 20,000 US$ in 2018. Every day lost in the shipyard for repairs would therefore have a significant economic impact (Clarksons Research, 2019).

To sum up, repair costs are, in general, lower than the loss of revenue due to a whale-ship collision. Direct costs of damages linked to the repairs may be worth from a few thousand to several hundreds of thousands of dollars depending on the work needed, the docking time, and the replacement of parts. Due to the lack of data on costs in the UD, we want to highlight that this section provided an overview of the potential costs, but did not provide a full assessment of the costs. Indirect costs involve the revenue loss endured by the company during the repair time. These costs might be higher, as it is linked to the freight rate and the type of merchandise (Stopford, 2009). We should stress out that the costs of repairs are most of the time covered by the ship's insurance, while this is not always the case for revenue losses (Stopford, 2009). In any case, insurance is not taken into consideration in the IMO decision-making framework (Sèbe et al., 2019).

4.4. IMPLICATION FOR WHALE-SHIP COLLISION MANAGEMENT

The assessment of damages and costs is crucial to managing more efficiently the whale-ship collisions. Lessons can be learned from the management of other wildlife-vehicle cases. While deemed low by the transportation industry, the damages, and their associated costs are often taken into account in balancing the benefits and costs (ICAO, 2009). This accounting helps decision-makers to define fund allocations for existing mitigation solutions, research and development (R&D), or even for fixing penalties (Allan, 2000; Dolbeer et al., 2015; Lienhoop et al., 2015; VerCauteren et al., 2006). The literature highlights several regional, national, or international policies advocating for the accounting of the damages in the management of wildlife-vehicle collisions.

Various collisions management initiatives exist at regional and national levels. For wildlife-car collisions, the costs of damages are often integrated into cost-effectiveness or cost-benefit assessments to define the most efficient mitigation solution depending on the study site characteristics (Gren and Jägerbrand, 2019; Santos et al., 2018; Seiler et al., 2016). More recently, investigations into wildlife-train collisions have been undertaken to define damages, delays, animal suffering, and driver stress caused by those events (Seiler and Olsson, 2017). The wildlife-aircraft collisions issue was identified early, as its management was motivated by some marking accidents, which lead to human losses (Dolbeer et al., 2015). Since 1988, an FAA National Wildlife Strike Database has been implemented in the U.S. to prevent human loss and aircraft damages (Devault et al., 2009). The assessment of the damages allows both to reduce the costs of mitigation solutions, and to reduce the environmental and human risks associated with collisions (Bissonette et al., 2008; Huijser et al., 2009a; Visintin et al., 2018).

Wildlife-aircraft collisions management is the most standardized one at the international level. In 1990, following the national database initiatives, the International Civil Aviation Organization (ICAO), which is the United Nations specialized agency *"whose mission is to achieve safe, secure, and sustainable development of civil aviation*", started getting involved in the collision issue and helped to standardize the management process (Devault et al., 2009; Dolbeer and Wright, 2009). Among other things, the ICAO maintains a bird-aircraft strike database (the ICAO Bird Strike Information System; IBIS), encourages the reporting of strikes and the damages related with them, and advocates for holistic risk assessments, through guidelines and standardized process, such as the Safety Management System (SMS) (Devault et al., 2009; Dolbeer and Wright, 2009; ICAO, 2017b, 2017a, 2012). Nowadays, these initiatives allow pro-active management of bird-aircraft collisions, such as better airport site selection, seasonal adaptation of the traffic, anticipated mitigation solutions, or government compensation (Anderson et al., 2015; Devault et al., 2009).

Following the ICAO approach, Sèbe et al. (2019) advocated for the involvement of the IMO into whale-ship collision management. The IMO represents the counterpart of the ICAO for maritime transport, as it is a United Nations specialized agency (Tarelko, 2012). IMO provides guidance for maritime-related risk assessment, through the so-called Formal Safety Assessment (FSA; IMO, 2018). FSA is a similar process to SMS, or other guidelines provided by the ICAO. Usually used for human safety or pollution (Haapasaari et al., 2015; Kontovas and Psaraftis, 2008), Sèbe et al. (2019) conceptualized the use of this framework to standardize the management of whale-ship collisions at an international level.

However, the lack of knowledge on damages associated with whale-ship collisions is a barrier to the successful implementation of one of the critical steps of the FSA, the Cost-Benefit assessment. This FSA step aims to identify the costs and benefits associated with the implementation of a mitigation solution. One of the benefits is the avoided cost, such as damage costs. Unlike other wildlife-vehicle collisions database, the IWC ship strike database is limited by the number of events recorded and by the lack of intelligence on the details of the events (e.g., speed, length, damage). Several factors explain those limitations. While some collisions might go unnoticed, many are underreported as shipping companies guidelines do not compel the crew to do it, or to avoid bad publicity (David et al., 2011; IWC-ACCOBAMS, 2012). Besides, the lack of coordination between organizations can be at the expense of the assessment of costs associated with whale-ship collisions. The IMO Casualty database (GISIS) does not provide any links to the IWC database, and hence whale-ship collisions do not appear into the scope of the IMO casualty events (Sèbe et al., 2019). Improvements in the collision reporting are therefore essential for the integration of the damages in the FSA, allowing for a holistic integration of the whale-ship management at the IMO level.

5. CONCLUSIONS AND PERSPECTIVES

The management of whale-ship collisions lacks of holistic risk assessment approaches. Similarly to what is done by the ICAO for wildlife-aircraft collisions, Sèbe et al. (2019) conceptualized a risk assessment approach to ship strikes using IMO's Formal Safety Assessment methodology. Nevertheless, limited knowledge hampers the application of such risk assessment techniques, especially related to the lack of information on the damages. Our works provide a first study on the subject by estimating the probability of ship damage. There is evidence that further research is required to improve the results. Better and standardized reporting would increase data availability and, thus, the robustness of the regression analysis. We acknowledge the fact that some other parameters such as the type of ship and species may provide more explanatory power for the model. However, the small size of our dataset prohibited the use of more than one variable in our prediction model (e.g., Peduzzi et al., 1996). Besides, as we have mentioned in the Introduction section, data after 2010 are not publicly available. There is, therefore, a clear need for more open and better data.

Furthermore, the extensive involvement of shipyards and shipping companies is needed to assess the costs of damages. Further research could also be undertaken for high-speed passenger ships, which have the highest damage probability, in order to prevent human losses. Lastly, the integration of the damages and the costs would provide a more transparent way for assessing the mitigation solutions' effectiveness, similar to what is performed on other wildlife-vehicle collisions.

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CHAPTER 3

An Assessment of the Shipping Industry's Preferences for Whale-Ship Collision Mitigation Solutions

"All roads lead to the IMO."

Geijer and Jones, 2015

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ABSTRACT

Whale-ship collisions represent a threat to some whale population survival. The shipping industry rarely adopts solutions to reduce the risk of collisions. This lack of compliance is partly due to the fact that previous work has failed to assess the economic and logistic impacts on the shipping industry of these solutions. Our work explored for the first time the logistical considerations affecting the adoption of whale-ship collision mitigation solutions by shipping companies. We used a choice experiment approach to assess the shipping industry's preferences for mitigation solutions, by questioning ship crews. Amongst other things, our results demonstrated a preference for avoiding a high-density whale area instead of reducing speed in it, and a requirement for upstream information to plan the journey depending on these areas. This Chapter could be used as guidelines for the implementation of mitigation solutions depending on situational characteristics.

Keywords: whale-ship collision, preference, shipping industry, choice experiment, avoidance, speed reduction

1. INTRODUCTION

Maritime traffic threatens marine mammals in many ways, directly or indirectly (Thomas et al., 2016). While chemical and noise pollution are often described as the main indirect threats of shipping to marine mammals (Abdulla and Linden, 2008), ships are also responsible for direct removals – deaths – of marine mammals, more specifically of whales, through ship strikes (Panigada et al., 2008; Pirotta et al., 2018). For whales, collisions with ships are one of the main threats to the survival of some populations (IWC-ACCOBAMS, 2012; Reimer et al., 2016). The overlapping of the habitats of these animal with maritime routes creates high collision risk areas – often associated with high mortality rates (Vanderlaan et al., 2009; Vanderlaan and Taggart, 2007). Furthermore, the current growth in maritime traffic, whether in terms of units, speed or engine capacity, tends to increase the level of risk of this threat in the coming years (Pirotta et al., 2018; Silber et al., 2012; Vanderlaan and Taggart, 2007).

In recent years, various solutions have been proposed to tackle the problem of ship collisions with whales (Pace et al., 2015). On one hand, technical solutions have appeared, mainly including whale detection tools, such as the Real-Time Plotting of Cetaceans System (REPCET) or the Boston passive acoustic network (Clark and Peters, 2009; Couvat et al., 2014). On the other hand, operational solutions have also been implemented such as speed reduction measures, traffic separation schemes (TSS), or areas to be avoided (ATBA) (Ritter and Panigada, 2019).

However, shipping companies have not always adopted these solutions, and especially the operational ones (Sèbe et al., 2019). Various factors can explain the lack of responsiveness on the part of shipping companies. Silber and Bettridge (2012) highlighted, as contributing factors, the lack of public recognition of the solution, or the lack of regulatory enforcement by the government. Recently, the absence of holistic approach when proposing solutions to the shipping industry's policy-makers has also been highlighted (Geijer and Jones, 2015; Silber et al., 2012). More precisely, the nonexistence of the integration of the logistic and economic dimensions in mitigation proposals is bewildering (Notarbartolo di Sciara, 2016; Sèbe et al., 2019, 2020). The integration of these dimensions would give an overall view to the decision-makers of the mitigation solutions' impacts on the shipping industry, a feature, which is currently missing from solution proposals. Indeed, the studies on whale-ship collision mitigation solutions focus, most of the time, on the theoretical effectiveness of the solutions, but very rarely take into account the economic and logistic dimensions of maritime traffic (Sèbe et al., 2019). Consequently, the applied effectiveness is often drastically different from the theoretical effectiveness, because of the shipping industry's low compliance with the proposed solutions.

Only a few attempts have been made to study the logistic and economic factors that may influence whether shipping companies adopt collision avoidance approaches or not. Mainly, these studies investigated the additional fuel cost incurred by the avoidance of an area or the reduction of speed in it. For example, Kite-Powell and Hoagland (2002) defined the costs associated with the reduction of speed around the Boston harbors (USA). In this study, the reduction in speed led to the loss of some ports of call. Indeed, the short distance between the regional ports did not make it possible to make up for lost time by increasing ship speed. The economic losses for harbors were estimated to be between $300,000 and $4,800,000 per year, depending on the size of the harbor. A similar study, conducted by Nathan Associates Inc. (2012), estimated the cost of collision reduction solutions at between $2,790,000 and $142,476,000 for the U.S. East Coast, based on different scenarios (e.g., speed reduction, dynamic management area). Recently, Gonyo et al. (2019) estimated the inventory carrying costs and the transportation costs of avoidance and speed reduction in the Channel Islands region (U.S. West Coast). This study evaluated a decrease in costs for the re-routing solution (1.6%-3.4%) and an increase in costs for the speed reduction solution (1.3%-2.0%). In parallel with these studies of the total costs of mitigation solutions, other studies focused on the cost of setting up and maintaining technical solutions (Silber et al., 2008a). These costs are often relatively low compared to company revenues (e.g., REPCET; Jacob and Ody, 2016), but they did not take into account operational costs associated with implementation (e.g., gas emission tax, fuel consumption, port of call loss; Stopford, 2009).

Thus, these studies often only partially reflect the economic dimension, which in turn would show an incomplete knowledge of the logistic dimension. Indeed, to the authors' knowledge, few studies have tackled the preferences of the shipping industries regarding whale-ship collision mitigation solutions depending on the logistical features required to implement the said solutions (e.g., Reimer et al., 2016). Before looking at the costs of any solution, the study of the logistic dimensions could be decisive to propose viable solutions for shipping companies, depending on the organization of the shipping industry. Some solutions may be impossible to implement because of delays in arrival in ports of call (Kite-Powell and Hoagland, 2002), the inability of mechanical engineers to adapt the engines to the solution requirements (*slow steaming*; Psaraftis and Kontovas, 2013) or because of specific navigational rules (e.g., COLREG; Eriksen et al., 2019) .

Our study aims to give first insights into how logistical considerations affect the adoption of whale-ship collision avoidance approaches by shippers. Because of a lack of economic and logistic data regarding the interactions between ships and whale-related collisions, we attempt to estimate the shipping industry's preferences for risk reduction solutions by using the Choice Experiment (CE) method. We propose mitigation solutions to the shipping industry – through their crew – accounting for situational characteristics in order to determine those factors that are most consequential in determining the adoption of avoidance methods and thus reflect the most significant features to take into consideration when proposing these solutions.

2. MATERIALS AND METHODS

2.1. CHOICE EXPERIMENT DESIGN

The CE methods are often used to assess the preferences of various stakeholders regarding environmental policies (Garrod et al., 2012). CE surveys present a series of alternatives – also known as choice sets – which encompass attributes describing a situation and a policy. The respondents must select the best alternative, in their opinion, allowing an implicit trade-off between the attributes (Hanley et al., 2002; Zander et al., 2013). The preference between attributes is then usually revealed through a willingness-to-pay value, which can be used as a monetary value, or as an indicator of the change in the utility (Garrod et al., 2012; Morey et al., 2008). Identifying relevant attributes that compose the alternatives proposed to respondents is crucial to designing a CE survey (Hanley et al., 2002). In our study, the attributes – and the levels that these take – were defined by consulting several experts on maritime traffic, whale conservation, and habitat modeling (Table 7).

Table 7. List of attributes and levels.

Attributes[a]	Number of levels	Levels[b]
Travel distance (TD)	4	100 nm; 300 nm; 500 nm; 700 nm
Time of reception of the information (TRI)	4	24h before port departure; 12h before port departure; 1h before port departure; 1h before arrival on AOI;
Size of the area of interest (AOI)	4	2.5 nm; 8 nm; 14 nm; 26 nm
Avoidance solution (AS)	2	Yes; No
Speed reduction solution (SRS)	4	No speed reduction (0%); 18kn to 14kn (20%); 23kn to 16kn (30%); 20kn to 12kn (40%)

[a] The variables names as used in the model are in parentheses

[b] The percentages of reduction in speed are in parentheses. These percentages were not visible in the questionnaire

Using the CE method, we propose two mitigation solutions to the shipping industry by applying a questionnaire to ships crews. The first one is the avoidance solution (AS) of a high-density whale area – or a high probability of collision area. The AS is a binary attribute composed of two levels, namely to avoid or not to avoid the area. The second solution is a speed reduction solution (SRS) into the area. The SRS attribute is composed of four levels representing speed reductions of 0%, 20%, 30%, and 40%. It should be noted that both AS and SRS can be combined in the same alternative, similar to that which is found in the literature (e.g., Vanderlaan et al., 2008).

To understand the contextual factors influencing preferences of the shipping industry for mitigation solutions, the alternatives are also composed of other attributes representing situational characteristics (Fig. 19). First, we offer different sizes – diameter – of the whale high-density area, hereafter referred to as the area of interest (AOI). The emergence of the Big Data and predictive models as a way of determining areas to avoid opens a new perspective for the prevention of vehicle-animal collisions (Hampton et al., 2013). Despite the many challenges ahead in the marine environment (Bohorquez et al., 2019), this type of tool is increasingly considered for whale-ship collisions in the coming years (Madon et al., 2017). Predictive modeling would then be used for alerting ships to the presence of an AOI, and the precision of the size of the area would increase with the development of technology. Of course, predictive modeling is not operational yet, but serves the purpose of justifying the size of the area in the narrative of the questionnaire. As mentioned, the levels describe area sizes, which have been selected to reflect the range of possibilities between the current and future predictive abilities (5-10 years).

For each choice alternative, an attribute represents the time of reception of the information (TRI) about the AOIs' characteristics (size and location). The TRI is crucial for the crew to take a decision on avoidance action possibilities. To define the levels of TRI, some logistical features were highlighted by informal interviews with captains, watch officers, and company environmental managers. These interviews underlined that, without a fleet center, the watch officers prepare the trip of the ship on the day of the journey or a day earlier. Then, the captain validates the journey one hour before departure. These times vary between companies, but the levels chosen for the study integrate this range of variability. Besides, one of the TRI levels was chosen to represent the possibility of receiving information at the last moment (1h before the arrival on the area), which can be the case with some observation networks' technologies (e.g., REPCET).

Finally, the last attribute is the travel distance (TD), which is an essential parameter of the shipping industry, as it defines the type of navigation a ship operates (Stopford, 2009). The travel distance levels selected represent a range of different types of navigation, from coastal navigation to long-distance travel.

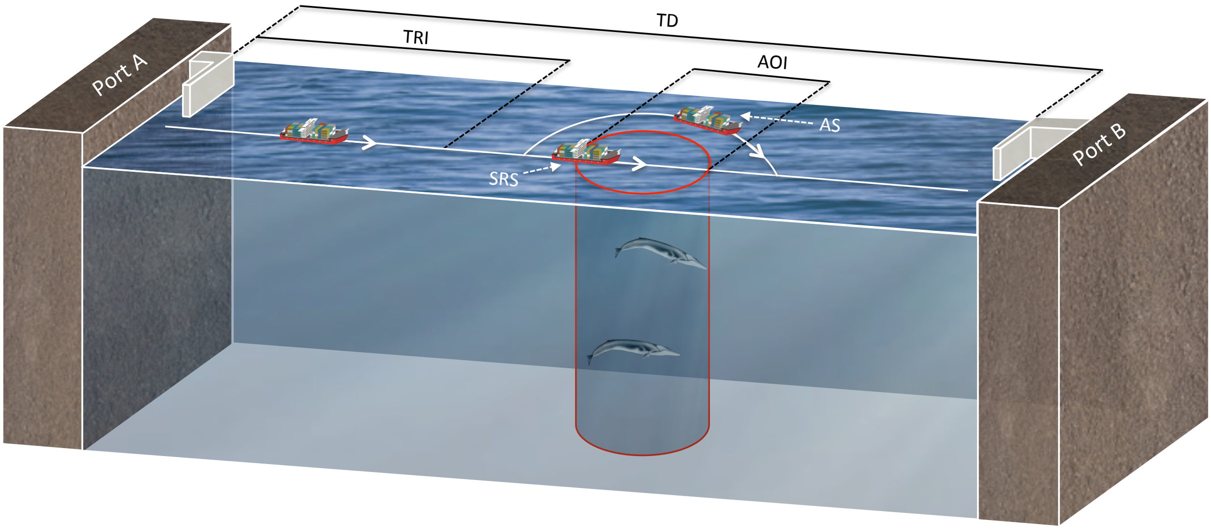

Figure 19. Conceptual illustration of the questionnaire. Note that the AS can be combined with the SRS in the questionnaire. TD = Travel distance; TRI = Time of reception of the information; AOI = Size of the area of interest; AS = Avoidance solution; SRS = Speed reduction solution. Conception: Authors.

The survey protocol was presented to a panel of maritime professionals who helped select and validate the attributes and their levels. The resulting experimental design – matrix of all the attributes' levels (Table. 1) – in our study is composed of $4 \times 4 \times 4 \times 2 \times 4 = 512$ alternatives. We then followed the different steps that are recommended and applied in the majority of the literature that uses the multi-attribute choice method to build an optimal design (e.g., Hanley et al., 2002).

First, a D-optimal fractional factorial design of 16 alternatives was generated[24] by the SAS® software using the OPTEX procedure (Edition 9.3). Then, we submitted a first questionnaire composed of these alternatives to several commanders, watch officers, and environmental managers to identify clarity issues or issues due to the authors' misunderstanding of the maritime traffic processes. Following that, the questionnaire was also submitted for testing to researchers from the AMURE Economics Laboratory to identify flaws in the survey protocol. Answers and comments from both phases were integrated in building the final optimal design. This optimal design is composed of 8 sets of 2 alternatives.

[24] This first design assumes all the parameters null.

Maritime companies – mainly from the south of France – were contacted, and the questionnaire was administered via the Internet by using the LimeSurvey platform (Limesurvey GmbH, 2019). The environmental officers of the shipping companies transferred the LimeSurvey questionnaire to commanders and watch officers. Therefore, this administration protocol allowed us to define precisely the sample size.

2.2. QUESTIONNAIRE

The questionnaire is composed of four parts. First, an introductory text explains the problem of whale-ship collisions. In this introduction, the logistical and economic issues that collision mitigation solutions could generate are also presented. At the end of this part, an explanation on how to fill in the CE questionnaire is provided. The second part of the questionnaire includes a first round of follow-up questions asked to determine the respondents' characteristics in order to be able to weigh the results of the CE. For example, questions about the respondent's job (captain or watch officer), the size of the vessel on which the respondent is deployed, and the ship category (tanker, bulk carrier, cargo ship - without passengers, cargo - with passengers) were asked. The third part of the questionnaire introduces the CE survey. For each choice set, respondents were asked to assume that they had performed both alternatives. Based on this principle, respondents were asked to answer the following question: "*In your opinion, which alternative represents the best compromise between the issues of maritime traffic and the protection of whales?"*. Three possible answers were possible *"Alternative 1"*, *"Alternative 2"*, and *"None of the alternatives are realistic"* – opt-out option to avoid pressure on respondents (Johnston and Abdulrahman, 2017; Fig. 20). Finally, in the fourth part, a Likert scale is proposed to assess the bias due to the attribute non-attendance (Hensher and Greene, 2010; Kehlbacher et al., 2013). The authors' contacts were also provided to the respondents so that they could share any comments on the questionnaire, or their activity.

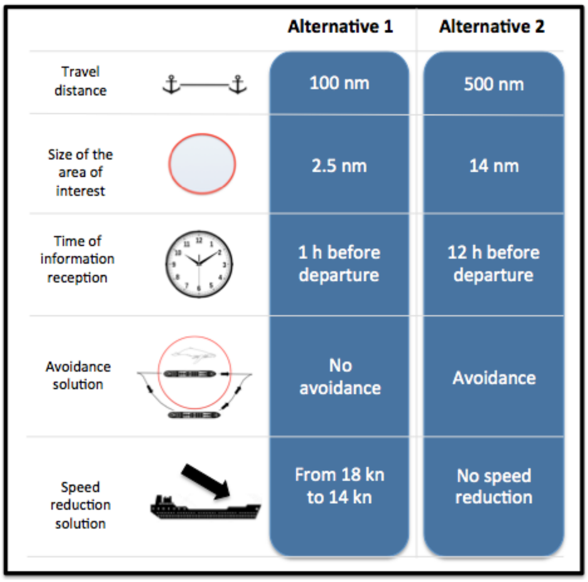

Figure 20. Example of a choice set. Conception: Authors.

2.3. ECONOMETRIC ANALYSIS OF CHOICE DATA

The developments in the random utility models' applications over the past two decades included four points (Manski, 2001; McFadden, 1974). The first one is (1) the unobservable heterogeneity of preferences (McFadden and Train, 2000). We select the specification of mixed logit of the form $\beta_j = b_j + \epsilon_j$, with $\epsilon' = (\epsilon_1, \dots, \epsilon_j, \dots, \epsilon_5)$ a Gaussian vector of zero mean and a var-cov matrix, Ω. This specification has a triple advantage of: testing the unobservable heterogeneity of preferences for each attribute *j* using the diagonal elements of Ω; identifying the interdependence of preferences between the different attributes *j* using the signs of the correlation coefficients deduced from this matrix Ω; and releasing the Independence of the Irrelevant Alternative (IIA) hypothesis (Hensher et al., 2005).

The second point deals with (2) the functional form of preferences. We opt for non-linear forms. We tested several forms by coding all quantitative attributes as qualitative explanatory variables (with modalities), and by applying linear, quadratic and logarithmic transformation. Given the estimates, we selected the quadratic specification, which is the most adequate according to the BIC criterion (Tables available upon request). For each quantitative attribute noted x_j, its utility is then specified in the form $U(x_j) = \beta_j x_j + \beta_{j2} x_j^2$, which can be concave/convex depending on the sign (-/+) of β_{j2} where $U_j = \beta_j + 2\beta_{j2}x_j$ informs on the variations in preferences according to the level of this attribute and to $\frac{-\beta_j}{2\beta_{j2}}$ its inflection point[25].

The third point (3) is to know if the level of importance or attention that respondents give to attributes when making their choice biases the protocol (Attribute Non-Attendance; ANA; Hess and Hensher, 2010; Hess et al., 2013). Two solutions are usually proposed. The first solution is to use adequate econometric specifications to take into account the importance of each attribute endogenously. This method, called inferred ANA, is applied when the authors fail to measure the importance given to each attribute by each individual when administering the survey. Scarpa et al. (2009), Hensher and Greene (2010), Hess et al. (2012), Hole (2011), Campbell et al. (2011), and Hensher et al. (2012) used discrete distributions (models with classes), and Hensher et al. (2013) proposed a more flexible specification allowing releasing the constraints of the parameters' equality between the classes (Hole et al., 2013). The second solution is to directly question respondents concerning the importance of each attribute (stated ANA; Alemu et al. 2013). Some authors added these questions after each set of alternatives (Puckett and Hensher, 2008), but this option has been criticized because it disrupts the individual's choice process and, consequently, complicates the questionnaire and the cognitive effort to complete it (Caputo et al., 2016; Carlsson et al., 2010; Colombo et al., 2013; Hess et al., 2008; Hess and Hensher, 2010). Also, this solution may lead to answers that are not consistent with the decision taken. For these reasons, in our study, we adopt the second solution by proposing respondents a 5-level Likert scale[26] for each attribute at the end of our questionnaire. The distribution of responses is given in Table 8. One can notice that the table is asymmetric and skewed to the right. This means that captains and watch officers give a high value, and, therefore more importance to all attributes. None of them give a value lower than 3 to all the attributes; 62.69% give at least the value 3 to the four discriminating attributes (TRI, AOI, AS, SRS). By only considering AS and SRS, 97% of the respondents give these mitigation solutions a value greater than or equal to 3, and 95.52% the value of 5 (Annex 5). These results indicate that prior discussions with maritime professionals helped build a robust questionnaire. Consequently, the attributes selected for this survey are relevant to the shipping industry and did not bias our study.

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[25] The level of the attribute at which preferences change directions of variation, increasing first, and then decreasing.

[26] Furthermore, disregarding the importance of each attribute in fact skews the results of the estimates and distorts the willingness to pay that can be deduced from them, in particular when the monetary attribute is ignored (Scarpa et al., 2009). Note that there is no monetary attribute in our assessment and there is no question of willingness to pay.

Table 8. Respondents' perception of the importance of the attributes.

	Not important	Slightly important	Moderately important	Important	Very important
Distance of travel	16.42%	16.42%	17.91%	37.31%	11.94%
Time of reception of the information	4.48%	19.40%	13.43%	34.33%	28.36%
Area of interest size	0.00%	1.49%	14.93%	43.28%	40.30%
Avoidance	2.99%	5.97%	11.94%	40.30%	38.81%
Speed reduction	4.48%	2.99%	14.93%	26.87%	50.75%

The fourth and final point deals with (4) the impact on the evaluation of the respondents' heterogeneity. During prior discussions with the maritime professionals, the only notable heterogeneity observed were the differences between captains and watch officers, and between the types of ship (e.g., cargo, tanker). Consequently, we re-estimated our different models by stratifying our sample according to these two variables, but only by retaining the majority group[27]. Few variations of the results are observed.

Based on these four points, in our study, each estimated model is based on a mixed logit model specification with a non-linear random utility function of the form $U_{ijt} = V_{ijt} + \varepsilon_{ijt}$ with $V_{ijt} = \beta_1 DIST_{jt} + \beta_{12} DIST_{jt}^2 + \beta_2 DELAIS_{jt} + \beta_{22} DELAIS_{jt}^2 + +\beta_3 ZONE_{jt} + \beta_{32} ZONE_{jt}^2 + +\beta_4 EVIT_{jt} + \beta_5 REDUC_{jt} + \beta_{52} REDUC_{jt}^2$. The vector $\beta = (\beta_1, \ldots, \beta_j, \ldots, \beta_5)'$ follows a multivariate Gaussian law $N(b, \Omega)$ of density $f(\beta / b, \Omega)$. The parameters of the model (b, Ω) are estimated by maximizing the expectation of the likelihood of the observations according to the density $f(.)$ of the unobservable heterogeneity, $L(b, \Omega) = E_{[f]}[L(\beta)]$. This expectation is calculated by the simulation method[28] proposed by Train (2003) using 500 random draws of the vector of the parameters β^r according to the density $f(.)$. The simulated likelihood $L^*(b, \Omega) = \prod_{i=1}^{n} \frac{1}{500} \sum_{r=1}^{500} [\prod_{t=1}^{8} \prod_{j=1}^{3} Pr(y_{it} = j|\beta^r)^{y_{it}}]$ with $Pr(y_{it} = j|\beta^r) = e^{V_{ijt}} / \sum_{l=1}^{3} e^{V_{ilt}}$ the probability that the individual i chooses the alternative j among the set of options t conditional on the fact that the preferences of this individual are subject to an unobservable heterogeneity characterized by density distribution $f(.)$.

27 The number of respondents is not large enough. However, this is not a sample. We cannot, therefore, venture to estimate our models for all the sub-groups, which therefore have very few respondents.

28 The estimation of this model is carried out using the Stata estimation procedure developed by Hole.

3. RESULTS

3.1. RESPONDENTS CHARACTERISTICS

The survey was conducted in June 2019. In total, 67 respondents completed the questionnaire, which represents 19.7% of the sample size. The sample frame was composed of captains and watch officers of leading French shipping companies (N=6). The proportion of captains and watch officers that responded to the questionnaire was similar (Tab. 9). No crew navigating on ships below 100m in length answered the questionnaire, which is not surprising as few of these ships are represented in the shipping companies surveyed. Most of the respondents belonged to cargo ships of sizes ranging from 100m to 250m (Fig. 21)

Table 9. Respondents characteristics expressed in percentages.

Respondents' characteristics	Share
Response rate	19.7%
Captains	44.8%
Watch officers	55.2%
Ship size - <50m	0%
Ship size - 50 to 100m	0%
Ship size - 100 to 150m	20.9%
Ship size - 150 to 200m	35.8%
Ship size - 200 to 250m	17.9%
Ship size - 250 to 300m	9.0%
Ship size - > 300m	14.9%
Tanker	9.0%
Bulk carrier	1.5%
Cargo ship without passengers	68.7%
Cargo ship with passengers	20.9%

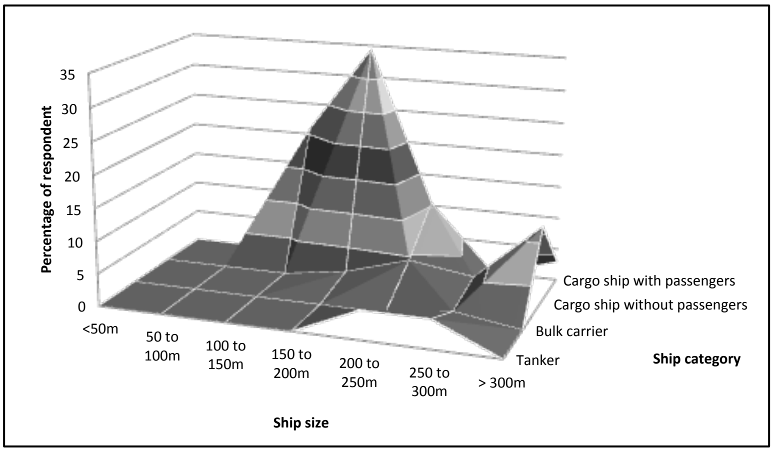

Figure 21. Ship characteristics of respondents. Conception: Authors.

3.2. MODEL RESULTS

Table 10 summarizes the best-fitted models. The model[29] *M1.a* is the most relevant one, because its BIC value is the lowest (1042). In this model, we have kept only the parameters that are significant depending on the bilateral Student's t-test (i.e., *p-value* does not exceed 10%). On one hand, the model *M1.a* shows that the preferences of the interviewees are subject to non-observable heterogeneity (i.e., the values of the standard deviations are significant for all the attributes). On the other hand, the model demonstrates that preferences are variable according to the attribute level.

[29] As mentioned in the previous section, other models have been estimated (Conditional Logit, Mixed Logit with different transformations of quantitative attributes). The results tables are large and provide little additional information. The BIC values are significantly higher (available to the readers upon request).

Table 10. Mixed logit results (online discrete choice experiment with 67 respondents, 1608 observations). In bold, the model selected for the study. Abbreviations: TD = Travel distance; TRI = Time of reception of the information; AOI = Area of interest; AS = Avoidance solution; SRS = Speed reduction solution.

	ML, U linear		ML, U quadratic				ML with only significant parameters			
Attributes	Independent		(M0.a) Independent		(M0.b) Dependent $\hat{\Omega}$		**(M1.a) Independent**		(M1.b) Dep. .$\hat{\Omega}$	
	$\hat{b}$ *(pvalue)*	$\hat{\sigma}$ *(pvalue)*	$\hat{b}$ *(pvalue)*	$\hat{\sigma}$ *(pvalue)*	$\hat{b}$ *(pvalue)*	$\hat{\sigma}$ *(pvalue)*	$\hat{b}$ ***(pvalue)***	$\hat{\sigma}$ ***(pvalue)***	$\hat{b}$ *(pvalue)*	$\hat{\sigma}$ *(pvalue)*
TD	0.00172	-0.0022	0.00277	0.00249	0.00262	0.00301	**0.00169**	**0.00261**	0.00210	0.00299
	(0.000)	(0.000)	*(0.044)*	*(0.000)*	*(0.068)*	*(0.000)*	***(0.001)***	***(0.000)***	*(0.000)*	*(0.000)*
TD²			-1.3e-06		-7.9e-07					
			(0.486)		*(0.689)*					
TRI	0.0284	0.0507	0.133	0.0592	0.145	0.0496	**0.141**	**0.0594**	0.144	0.0516
	(0.011)	(0.001)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.005)*	***(0.000)***	***(0.000)***	*(0.000)*	*(0.004)*
TRI²			-0.0042		-0.0048		**-0.00464**		-0.00470	
			(0.0059)		(0.003)		**(0.000)**		(0.000)	
AOI	-0.0345	0.0478	-0.0764	0.0576	-0.0712	0.0543	**-0.0700**	**0.0584**	-0.0810	0.0466
	(0.010)	(0.051)	*(0.032)*	*(0.009)*	*(0.059)*	*(0.005)*	***(0.000)***	***(0.009)***	*(0.000)*	*(0.028)*
AOI²			0.00041		-0.00037					
			(0.751)		*(0.785)*					
AS (coding effect)	0.113	0.586	0.385	0.674	0.413	0.668	**0.391**	**0.653**	0.439	0.549
	(0.303)	(0.000)	*(0.005)*	*(0.000)*	*(0.006)*	*(0.000)*	***(0.002)***	***(0.000)***	*(0.002)*	*(0.035)*
SRS	-0.0248	0.0627	0.0738	0.0847	0.0742	0.0354	**0.0740**	**0.0863**	0.0783	0.0420
	(0.013)	(0.000)	*(0.005)*	*(0.000)*	*(0.008)*	*(0.039)*	***(0.001)***	***(0.000)***	*(0.002)*	*(0.029)*
SRS²			-0.0029		-0.0033		**-0.00310**		-0.00326	
			(0.000)		*(0.000)*		***(0.000)***		*(0.000)*	
BIC	1065		1056		1103		**1042**		1091	

Regarding situational characteristics attributes, results show that the crew preference positively increases with distance travelled (TD) attribute (Fig. 22). In other words, the greater the distance, the less reluctant the crews of surveyed companies are to implement a whale-ship collision mitigation solution. Similarly, the preferences for the time of reception of the information (TRI) are positive up to an inflection point at 15.19h. This result means that the crew prefers to have upstream information about an area of interest (AOI) up to a point (15.19h) where there is no added value of having more time to prepare the journey. Not surprisingly, the crew prefers AOI limited in size. Each additional nautical mile to the AOI results in a loss of utility of 0.00345.

For the whale-ship mitigation solutions, we find that the shipping industry is well aware of the underlying issues and is not reticent to either solution (the estimated parameters are positive and more than 99% reliable). However, their preferences for speed reduction sharply decreases when the reductions imposed are too high – exceeding the inflection point of 11.94% of speed reduction – and become negative when they exceed 30.39%. We can use our estimates to compare the trade-offs between the preferences of the two mitigation solutions. In Figure 22, the curve of the utility function of the attribute SRS is higher than its value for the attribute AS for speed reductions between 7.9% and 16% (the two roots of polynomial $(SRS) = U(AS) \Leftrightarrow 0.074 \times SRS - 0.0031 \times SRS^2 = 0.391$). This means that avoidance is preferable in these cases (when the speed reductions are too high above 16 and too weak below 7.9). Undoubtedly, avoidance is an opportunity for ships to take other alternative shipping routes that are just as beneficial to their commercial activity.

a)

Attribute	Correlated with	Preferences sign (inflection point)
TD	TRI (positively) AOI (negatively)	+
TRI	SRS (positively)	+/- (15.19)
AOI	AS (negatively)	-
AS	AOI (negatively) SRS (negatively)	+
SRS	TRI (positively) AS (negatively)	+/- (11.94)

b)

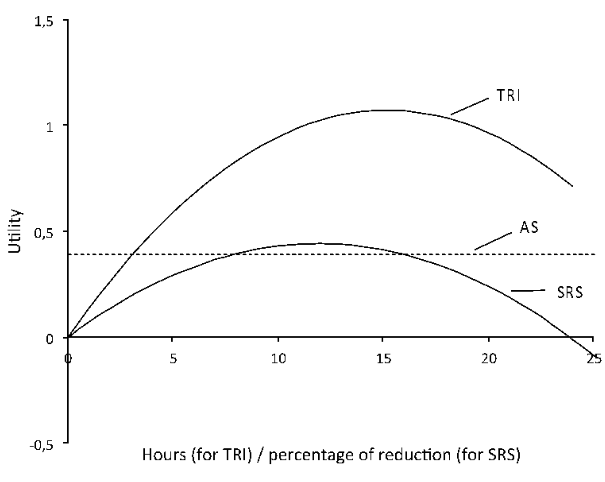

Figure 22. Correlation and variation in the utility of the attributes. The AS attribute in the illustration is constant (a). Its variation is dependent on other attributes (see (b)). Conception: Authors.

Further, our mixed logit specification *M1.b* with a dependent multivariate Gaussian distribution allows estimating the correlation between attributes due to the unobservable heterogeneity of preferences It should be noted that, we refer to the results of this model without forgetting that its BIC value is higher than the one from the *M1.a* specification ($BIC_{(M1.a)} = 1042 < BIC_{(M1.b)} = 1091$). For mitigation solutions, these first results highlight a significant negative correlation (more than 99% reliable depending on the bilateral Student's t-test), which demonstrates a form of substitutability between the two solutions. In other words, maritime transport professionals prefer when they are given a choice between the two solutions. Depending on the situational characteristics, they can decide on their own to avoid or reduce their speed.

4. DISCUSSIONS AND CONCLUSIONS

4.1. SHIPPING INDUSTRY'S PREFERENCES

In this research, we performed a first empirical evaluation of the shipping industry's preferences for mitigation solutions based on the Choice Experiment design. In particular, we targeted the ships' crew, composed of captains and watch officers. The crew takes navigational decisions based on their training, international regulation, but also based on instructions of its companies regarding schedules and economic aspects (Lloyd's Register, 2015; Sèbe et al., 2019). Consequently, their choices reflect the overall policy of the shipping industry; the crew preferences being instructive of the shipping industry behavior regarding mitigation solutions.

The avoidance solution appears to be the ship crews' most appreciated solution – with some exceptions. This observation confirms the observed compliance in the literature regarding these kinds of solutions. As mentioned before, the avoidance of an area of interest can be undertaken either by TSS or ATBA. Regarding TSS, Lagueux et al. (2011) exposed 96.2% of compliance with recommended routes in the right whales' southeast US calving ground (in Georgia and Florida). Similarly, McKenna et al. (2012) showed compliance between 79% and 89% with the TSS for blue whales protection off the coast of southern California. The compliance with ATBA also seems to confirm our results; Vanderlaan and Taggart, (2009) indicating 71% of compliance with the voluntary ATBA in Roseway Basin right whale habitat. The speed reduction solutions do not meet the same level of compliance. Several studies highlighted compliance below 33%, and even a case with 1% of compliance (Freedman et al., 2017; Lagueux et al., 2011; McKenna et al., 2012; Silber et al., 2012; Wiley et al., 2008). An exception should be highlighted in St. Lawrence Estuary with a 72% compliance with speed reduction, mainly through the collaboration between stakeholders (Parrott et al., 2016). Note the potential increase in compliance due to the mandatory status of a solution (e.g., 9.8-23.2% to 75%; SRS; Lagueux et al., 2011) or the incentives to comply with it (e.g., 13% to 77%; SRS; McKenna et al., 2012). Also, Weinrich et al. (2010) noted that the avoidance solution was preferred in cases of last-minute decisions.

Economically, the preference for avoidance appears to make sense. Gonyo et al. (2019) studied the variation in costs between the avoidance and speed reduction solutions. While the implementation of the speed reduction solution decreases transportation cost – linked to fuel consumption –, the inventory carrying costs do increase. In opposition, there will be a slight decrease in the inventory carrying and the transportation costs for the avoidance solution. These variations are mainly due to the management of the additional transit time. On one hand, the speed reduction solution involves a decrease in speed in a given area of interest. This decrease will positively impact the ship because the fuel consumption increases with speed (Bialystocki and Konovessis, 2016). Though, as a result of speed reduction, the transit time will be longer, and it would require increasing the speed outside the area of interest to offset lost time. This variation between *slow steaming* and operational speed might require a reconfiguration of the engine to achieve an efficient lower power output (Psaraftis and Kontovas, 2013). Furthermore, the distance between harbors might be too short to offset lost time, and supplementary constraints might appear (e.g., delays of arrival in port, disrupted land transportation; loss of docking; Kontovas and Psaraftis, 2011; Nathan Associates Inc, 2012). These parameters lead to an increase in inventory carrying costs. On the other hand, the avoidance solution often increases the transit time by increasing the distance traveled. However, a slight increase in operational speed can offset lost time, which explains the low additional costs.

Logistically, our results highlight the importance of receiving early information (TRI) about the area of interest characteristics, especially for watch officers. The more the information is received in advance, the more it will impact the utility function positively. When we know the role of each crew member (e.g., captain, watch officer; Annex 5), we underline that the TRI is significant for the watch officers, but not for the captains. These results confirm the hypothesis collected during informal interviews regarding voyage planning; the watch officers formulate a voyage plan at least 12 hours before departure, and the captain validates it around one hour before departure. Our results confirm this feature, as the delay of reception of the information is more important to watch officers than for captains. Besides, regulations impose that the voyage plan *"should be approved by the ships' [captain] prior to the commencement of the voyage"* (IMO, 1999), and the captain should also validate significant modifications during the voyage (Varin, pers. comm. 2019). It is then pivotal that watch officers know the information in advance in order to organize the journey, and propose solutions to the captain. Our results are in line with the ones of Reimer et al. (2016), which demonstrated a preference for receiving information before leaving port, or within a few hours of arriving at the AOI (respectively 53% and 35% of the respondents). However, Reimer et al. (2016) did not find a clear consensus on the best time to receive the information. In light of our results, this lack of consensus is explained by the fact that Reimer et al. (2016) did not make a distinction between captains and watch officers. Moreover, our study quantified the maximum reception time of information. As mentioned before, at one point – inflection point – there is no added value of having more time to prepare the journey (15.19h).

Also, not surprisingly, whatever the solution selected; the utility function increases with the distance covered. This feature can be decisive for whale protection. For example, Mediterranean fin whales exhibit a coastal distribution in summer between France, Italy and Corsica, where whales are at risk of collisions with short-travel passenger ships (Jacob and Ody, 2016). In short-travel configuration, the avoidance would meet more compliance from companies than the speed reduction solution. However, in winter, this population is partly suspected to inhabit more offshore waters, such as the ones of Western Sardinia (Laran et al., 2017). In this area, ships travel longer distances, between, for example, France and Africa. Our results suggest that, if habitat modeling confirms fin whales' offshore winter distribution, the implementation of mitigation solutions – even speed reduction – should be effective thanks to potential high compliance.

4.2. IMPLICATIONS FOR CONSERVATION

Conservation scientists often propose the most effective theoretical solution when a collision threat is identified. Speed reduction is one of the best-identified solutions (Parrott et al., 2016; Vanderlaan and Taggart, 2007). This solution acts directly on the probability of mortality, whereas the avoidance solution acts on the probability of encounter – occurrence (Vanderlaan et al., 2008a). Hence, the implementation of speed reduction guarantees having a positive impact on the risk of lethal collision, even in a data-poor environment. On the contrary, to be effective, avoidance solutions require an extensive understanding of whale habitat and distribution, which is not always the case. Therefore, conservation scientists are more prone to advocate for speed reductions, despite some recent reconsiderations on the subject (Gonyo et al., 2019; IWC, 2019).

Though, while theoretically effective, the applied effectiveness of the speed reduction solution is often limited. In the literature, the risk reduction induced by solutions is often expressed by assuming full compliance from the shipping industry (e.g., Gonyo et al., 2019; Silber and Bettridge, 2012; Vanderlaan et al., 2008; Wiley et al., 2011). However, as exposed before, this level of compliance is rarely met. In opposition to speed reduction, the avoidance solution often meets the shipping industry's compliance, and therefore, might have a higher applied effectiveness.

The shipping industry's preferences expressed in our study advocate for the use of the avoidance solution instead of speed reduction. The primary preferences of the shipping industry and of the conservation scientists are therefore at odds. As a consequence, conservation scientists should integrate the shipping industry's preferences before presenting a mitigation solution to achieve more effective protection of whales. For short journeys, such as the ones in the summer habitat of Mediterranean fin whales, avoidance solutions should prevail, especially for ships providing cabotage services. This solution is logistically more efficient to offset time lost (Brouer et al., 2013). According to our results, for offshore navigation, the type of mitigation solution matters less to the shipping industry, as the long distances allow offsetting the lost time.

However, to be able to offset the cost of any mitigation solutions, ships need to be noticed in advance of the characteristics of area of interest. The enhancement of the current whale habitat models towards more dynamic models is required to achieve this kind of notification. Whale habitat models are increasingly sophisticated with the integration of biotic (e.g., whale acoustic and observation) and abiotic (e.g., bathymetry; chlorophyll) parameters (Becker et al., 2019; Mannocci et al., 2015; Sigourney et al., 2020). The emergence of Big data opens-up the possibility of frequent habitat updates or even near real-time updates (Hampton et al., 2013; Madon et al., 2017; Pimm et al., 2015). Of course, the technology leading to a predictive tool is not yet operational, and, meanwhile, other promising options of alerting can be implemented such as acoustic networks (e.g., Boston harbor; Ritter and Panigada, 2019) or observation networks (e.g., REPCET; Couvat and Gambaiani, 2013). To be noted that Reimer et al. (2016) showed crew' preference for receiving the information on the Automatic Identification System (AIS). The AIS presents the advantage of not being disruptive of the crews' activities. Nevertheless, several limitations to the incorporation of whales' areas of interest to the AIS are yet to overcome (McGillivary et al., 2009).

While our study highlights the required features for mitigation solutions, the resulting compliance with them might still be low if their implementation is not standardized. This aspect has recently been highlighted for gas emission reduction solutions. The shipping companies appear to approve speed reductions for decreasing these emissions, but request a clear regulation to act (Anonymous, 2019; Psaraftis, 2019). A regulation would dictate the implementation of the solution to the entire fleet of a region, and avoid the loss of competitiveness that countries' unilateral implementation would bring (Gritsenko and Yliskylä-Peuralaht, 2013). This reasoning applies to whale-ship collision solutions, as expressed by a former captain at the International Conference on Marine Mammal Protected Areas (ICMMPA, 2019). During this conference, this former captain criticized the implementation of a mitigation solution (REPCET) to only French ships: *"We can't have a rule that applies to a French vessel and not to an Italian vessel, this is discrimination. We need solutions at the International Maritime Organization level"* (Varin, pers. comm. 2019).

The International Maritime Organization (IMO) represents then a promising way of implementing these recommendations. The IMO is a United Nations agency, which regulates all aspects of maritime safety and protection of the marine environment (Silber et al., 2012) and is recognized as the authority in international shipping (Geijer and Jones, 2015). The IMO *"produces conventions which become law when they are enacted by each maritime state"* (Stopford, 2009). While the implementation of voluntary mitigation solutions often meets low compliance, the IMO's involvement through mandatory or recommended measures – mostly TSS and ATBA – has been proven to be effective in increasing the compliance (Geijer and Jones, 2015). Furthermore, as the Roseway Basin seasonal ATBA exhibits, the IMO recommendations can be flexible (IMO, 2007a). This flexibility can be used to provide the best-suited solutions based on the preferences of the shipping industry and whale habitat dynamics.

Our study may also contribute to other IMO mechanisms that can be adapted to the collision management, such as Particularly Sensitive Sea Areas (PSSA). A PSSA is *"an area that needs special protection through action by IMO because of its significance for recognized ecological, socio-economic, or scientific attributes where such attributes may be vulnerable to damage by international shipping activities"* (IMO, 2006c) Crew' preference can be used, for example, in the current reflection for a PSSA in the Mediterranean (IMO, 2016a). This PSSA should cover a large part of the Western Mediterranean, and could – according to guidelines – combine several solutions inside the PSSA. Depending on the different types of navigation within the potential PSSA, various solutions can be considered based on the preferences of the shipping industry to optimize their compliance.

4.3. FURTHER RESEARCH

Further research is required to improve our understanding of the shipping industry's preferences. For example, our results highlight that the utility for small speed reductions, below 7.9%, is inferior to moderate speed reductions – 7.9% to 16% – for which the utility is even superior to the avoidance solution. These preferences might be linked to how the ships and the industry operate (Eriksen et al., 2019; Kite-Powell and Hoagland, 2002; Psaraftis and Kontovas, 2013). These results might confirm that the shipping industry prefers to be given a choice, rather than to have a solution imposed.

In addition, heterogeneity factors should be investigated to refine our results. Most of the survey respondents in our study operate little to medium-size cargo ships, which are typical of short-haul trips (Fig. 2; Jacob and Ody, 2016). Consequently, respondents' answers for longer journeys might be biased. Also, on one hand, more than 20% of the respondents operate passenger ships that are more likely to undergo damages following whale-ship collision (Sèbe et al., 2020) and, therefore, the crew presumably might be more careful in avoiding obstacles, such as whales. On the other hand, passenger ships' contribution to whale deadly collisions is known to be higher than that of other ship categories (Jacob and Ody, 2016), leading to a higher focus of conservationists on passenger ships. Hence, the crew of other categories might be less aware of the whale-ship collision issue, because conservationists raised less awareness of the crew in these categories. These heterogeneity factors – amongst others – might have affected our results and require further investigation.

Our survey was carried out on a limited number of respondents – mainly due to the limited sample frame that represents captains and watch officers. Contacting other shipping companies might be decisive to overcome the lack of heterogeneity in respondents. Also, while we tested several specifications in our study, other specifications might be adapted to this kind of survey (e.g., endogenous NAA; Hole et al., 2013).

4.4. CONCLUDING REMARKS

To sum up, our study highlighted some features to define best-suited whale-ship collisions mitigation solutions. The solution that might reach the highest compliance from the shipping industry is the avoidance one. In order to improve the solutions' effectiveness, upstream information of the area of interest is required. Also, a higher resolution of the size of the area would improve compliance. These features emphasize the need for improved habitat modeling, or other tools to define the areas of interest. With time, our results could be used as guidelines to solution proposals based on the situational characteristics of a studied site.

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CHAPTER 4

Whale Human-Induced Direct Mortality in Mediterranean Sub-Populations: How Much is too Much?

"The loss of biodiversity is the only truly irreversible global environmental change the Earth faces today."

R. Dirzo and P. Raven, 2003

Recommended citation:

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ABSTRACT

Human activities threaten the Mediterranean fin (*Balaenoptera physalus*) and sperm (*Physeter macrocephalus*) whale sub-populations. Quantifying the severity of these threats to whale populations is for the most part challenging due to lack of applicable data. The semi-enclosed characteristic of the Mediterranean basin provides a unique opportunity to bypass some of this data shortage. In this Chapter, we applied the carcass recovery approach to the Mediterranean stranding databases in order to assess the number of whale human-induced direct mortality (entanglement and collisions). We used this approach to compare our calculated mortality to management rules (Potential Biological Removal and Critical Reference Point) to define the severity of human activity on the Mediterranean sub-populations. Results show that collisions and entanglements alone may be responsible for the decline of the Mediterranean fin whale sub-population, and that further research is necessary to determine how human-induced indirect mortalities (e.g., pollutant, prey depletion) affect the sperm whale population. We urge the ACCOBAMS to revise its management rules for fin whales, and are in total accord with previously published work, which argues in favor of a reassessment of the IUCN status of this sub-population.

Keywords: Mediterranean, fin whale, sperm whale, Human-Induced Direct Mortality, management rule, acceptable risk

1. INTRODUCTION

The Mediterranean Sea is considered to be a biodiversity hot spot (Pace et al., 2015), hosting 6.3% of the world marine biodiversity (Bianchi and Morri, 2000) with a high number of endemics (Coll et al., 2010). This biodiversity is under threat by human activity. The Mediterranean Sea is one of the busiest marine areas in the world, with 13% of the world sea trade on only 0.8% of the global ocean surface (IWC-ACCOBAMS, 2012). The impact of human activity, exacerbated by the semi-enclosed characteristic of the basin, has rendered the Mediterranean Sea one of the most degraded seas worldwide (Claudet and Fraschetti, 2010; Coll et al., 2010; Halpern et al., 2008). Human activity affects biodiversity at all taxonomic levels, including that of marine mammals.

Mediterranean marine mammals represent 18.4% of the world's marine mammal biodiversity (Bianchi and Morri, 2000; Notarbartolo di Sciara, 2016; Pace et al., 2015). Several local and regional initiatives have been implemented to mitigate the human impact on these species. At a local level, the Pelagos Sanctuary is the largest marine protected area (MPA) in the Mediterranean dedicated to the protection of marine mammals. The sanctuary was enforced in 2002 to protect a high diversity area for marine mammals in the Northwestern part of the Mediterranean (Notarbartolo di Sciara et al., 2008). The management plan of the sanctuary delineates its purpose of *"catalyzing voluntary measures by the French, Italian and Monegasque governments to minimize environmental impacts on the area; and providing a demonstration model for large scale, ecosystem-based management, high seas MPAs, the utility of regional seas agreements, the use of species as "umbrellas" to protect whole ecological communities, and the role of individuals in carrying forward a conservation vision"* (Notarbartolo di Sciara et al., 2008). Other marine protected areas take marine mammals into consideration in their management plans, but are not dedicated to the protection of these species. At a regional level, the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) also focuses on increasing whale protection, acting as a facilitator for the implementation of protection measures, or of more local conservation schemes (IWC-ACCOBAMS, 2012).

These organizations are essential for the protection of marine mammal populations, but they often have limited means, relying primarily on international cooperation (e.g., IWC-ACCOBAMS, 2012). One of the best-known applied measures supported by ACCOBAMS and Pelagos is the Real-Time Plotting of Cetaceans System (REPCET); REPCET creates a network for ships to communicate whale sightings in order to avoid collisions (Couvat et al., 2016).

Despite these initiatives, the ever increasing amount of human activity in the Mediterranean Sea intensifies the pressure on marine mammals, particularly on the fin (*Balaenoptera physalus*) and sperm (*Physeter macrocephalus*) whale sub-populations (Claudet and Fraschetti, 2010; Halpern et al., 2015; Notarbartolo di Sciara, 2016; Pirotta et al., 2018).

The Mediterranean sub-populations of fin and sperm whales are amongst the most threatened worldwide (Avila et al., 2018). Genetic evidence indicates that the Mediterranean sub-populations of fin and sperm whales are isolated from their conspecific Atlantic populations (Notarbartolo di Sciara, 2016). This genetic isolation contributes to the lowered resilience of the Mediterannean sub-populations to human threat relative to other species in enclosed habitats (Pace et al., 2015). The enclosed nature of the Mediterranean Sea further exacerbates threats faced by whales (Pace et al., 2015; Pinzone et al., 2015). Threats can be divided into two types: Human-Induced Direct Mortality (HIDM) and Human-Induced Indirect Mortality (HIIM). Primary factors causing HIDMs in the Mediterranean Sea include direct death caused by collisions with ships (Ritter and Panigada, 2019) or entanglement in fishing gear (Notarbartolo-Di-Sciara, 2014). The main threats causing HIIMs, are those that affect the habtitat requirements of the sub-populations. These threats include anthropogenic noise (Castellote et al., 2012), physical and chemical pollution (De Stephanis et al., 2013; Squadrone et al., 2015), prey depletion due to overfishing or seismic activities (Mazzariol et al., 2011; Douglas J. McCauley et al., 2015) and climate change (Nunny and Simmonds, 2019). HIDM contributes to whale mortality whereas HIIM increases whale morbidity by decreasing survival probabilities (e.g., survival, reproductive success; Curtis et al., 2015). These HIDM and HIIM threats, coupled with the characteristic of the Mediterranean basin, resulted in the classification of the Mediterranean sperm and fin whale sub-population status as, respectively Endangered and Vulnerable according to the IUCN Red List (C2a(ii); Notarbartolo di Sciara et al., 2012; Panigada and di Sciara, 2012). Furthermore, there are good reasons to revise the status of the Mediterranean fin whale to a more endangered classification (Notarbartolo di Sciara, 2016; Panigada and di Sciara, 2012).

Quantifying human impact is often challenging despite a scientific consensus of the urgency of the situation. HIDM hot spots are usually well documented (e.g., Frantzis et al., 2019), but the impact of these identified hot spots on (sub-)population is rarely assessed (Brown et al., 2019; Curtis et al., 2015; Lonergan, 2011; Rockwood et al., 2017).

The nature of the Mediterranean basin offers a unique opportunity to estimate the severity of human-induced mortality. Usually, when whales die, their carcasses either sink or drift. The sunken carcasses represent lost mortality data. Carcasses that drift however will eventually wash up on shore. Carcasses can drift long distances from their initial place of death, obfuscating the origin of the whale's original population and where the strike may indeed have occurred (Jung et al., 2016; Peltier et al., 2016; Peltier and Ridoux, 2015). Conversely, the fact that the Mediterranean is semi-enclosed, ensures (1) a low probability factor that a carcass would drift outside the basin; and (2) a limited immigration and emigration of whales (Geijer et al., 2016; Notarbartolo di Sciara et al., 2016); consequently, when a whale strands on the Mediterranean coasts, there is a high probability that it belongs to the Mediterranean sub-population. These unique characteristics are well suited for the use of the carcass recovery rate approach (Williams et al., 2011) in the Mediterranean to estimate whales HIDM and provide more reliable data than that obtained in an open basin.

The objective of this chapter is to quantify the severity of the impact of HIDM on the Mediterranean fin and sperm whale sub-populations by using the unique features of this sea. We use an approach based on the carcass recovery rate to estimate the HIDM, and then we estimate commonly-used management rules[30] to assess the severity of the impact of HIDM on the sub-populations.

2. MATERIALS AND METHODS

Stranding data and the carcass recovery rate are used here to estimate the number of HIDM for Mediterranean fin and sperm whales. Our approach is based on the studies of Heyning and Dahlheim (1990), Kraus (2005), and Williams et al. (2011).The semi-enclosed nature of the Mediterranean Sea allows us to assume that stranded whales belong to the corresponding Mediterranean sub-population (i.e., closed population with no immigration or emigration).

[30] Management rules here refer to conservation targets that influence policy decisions (Lonergan, 2011). This terminology was chosen to account for the heterogeneity in the literature regarding conservation targets, that can be called "Limit Reference Points" (Curtis et al., 2015), critical values (Caswell et al., 1998), or threshold (ACCOBAMS, 2016).

Natural mortality in strandings

First, we estimated the annual mortality in the stranding data based on the information provided by the Mediterranean Database of Cetacean Strandings (MEDACES)[31]. Second, given that the causes of mortality are not indicated in the MEDACES database (Pace et al., 2015), we contacted the Mediterranean Stranding Networks (MSN) of every country to obtain cause of death information (ACCOBAMS-ECS, 2018; Becker et al., 1994). We estimated the proportion of entries in the MSN database representing individuals that died from natural causes and applied it to the number of strandings observed in the MEDACES database in order to define the annual number of strandings due to natural death in the Mediterranean $M_{nat_{strand}}$.

Carcass recovery rate and total HIDM

The estimated number of strandings due to natural death $M_{nat_{strand}}$ was then used to estimate the carcass recovery rate. The carcass recovery rate represents the number of stranded whales that died from natural causes relative to the total theoretical number of natural deaths in the sub-population (Taylor et al., 2007; Williams et al., 2011; Equation 1).

$$\alpha_i = \frac{M_{nat_{strand,i}}}{M_{nat_{0,i}}} \qquad (1)$$

where α_i is the carcass recovery rate of sub-population *i*; $M_{nat_{strand,t,i}}$ is the number of dead whales of sub-population *i* that stranded of natural causes at year *t*; and $M_{nat_{0,t,i}}$ is the the total theoretical number of natural deaths in the sub-population *i* at year *t*.

This value, the theoretical number of deaths in the sub-population $M_{nat_{0,t,i}}$, is calculated as follows:

$$M_{nat_{0,t,i}} = N_{t,i}(1 - s_{0,i}) \qquad (2)$$

where $N_{t,i}$ is the abundance of sub-population *i* at time *t*; and $s_{0,i}$ is the theoretical survival rate of sub-population *i*. Like other studies using the carcass recovery rate (Heyning and Dahlheim,

[31] The MEDACES was created under the Barcelona Convention, and extended to the ACCONAMS area. This is a database of cetacean strandings reported by Mediterranean Stranding Networks (MSN) from 1980 to 2016. This database is the best source of information to estimate the number of strandings at the Mediterranean scale (Perrin and Geraci, 2008)

1990; Kraus, 2005; Williams et al., 2011), theoretical survival rates for fin and sperm whales are respectively set at 0.96 and 0.986 (standard reference parameters from Taylor et al., 2007).

We assume that in sub-population *i*, the carcass recovery rate α_i for whales that died of natural causes will be equal to the carcass recovery rate for individuals dying from anthropogenic causes. We also assume that α_i does not vary in time. Therefore the total annual number of HIDM of sub-population *i*, is estimated by dividing the annual number of stranded whales of sub-population *i* that died of HIDM by the carcass recovery rate estimated for the sub-population *i*, such as in Equation 3:

$$M_{HIDM_{t,i}} = \frac{M_{HIDM_{strand,t,i}}}{\alpha_i} \quad (3)$$

Where $M_{HIDM_{t,i}}$ is the annual number of whales of sub-population *i* that died of HIDM; and $M_{HIDM_{strand,t,i}}$ is the observed number of stranded individuals of sub-population *i* that were reported dead of HIDM causes[32] at year *t*.

Management rules

We then quantified the impact of these HIDM on the sub-populations by applying management rules (Curtis et al., 2015). Management rules are defined as conservation targets that influence policy decisions (e.g., Limit Reference Points; Curtis et al., 2015). We used two management rules in our study: the Potential Biological Removal (PBR) and the Critical Reference Point (CRP) (Caswell et al., 1998; Wade, 1998). Each one describes a different conservation target.

The PBR corresponds to *"the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population"* (Wade, 1998). The PBR is calculated as follows:

$$PBR_{t,i} = N_{min,t,i} \ {}^{1}\!/_{2} \ R_{max,i} \ Fr_{t,i} \quad (4)$$

with $N_{min,t,i}$ the minimum population estimate of the sub-population *i* at year *t*, the recovery factor $Fr_{t,i}$ of the sub-population *i* at year *t*, initially set at 0.1 for the Mediterranean fin and

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[32] $M_{HIDM_{strand,t,i}} = M_{tot_{strand,t,i}} - M_{nat_{strand,t,i}}$, where $M_{tot_{strand,t,i}}$ is the total number of dead whales of sub-population *i* that stranded (MEDACES) at the year *t*; and $M_{nat_{strand,t,i}}$ is the number of dead whales of sub-population *i* that stranded of natural causes at the year *t*.

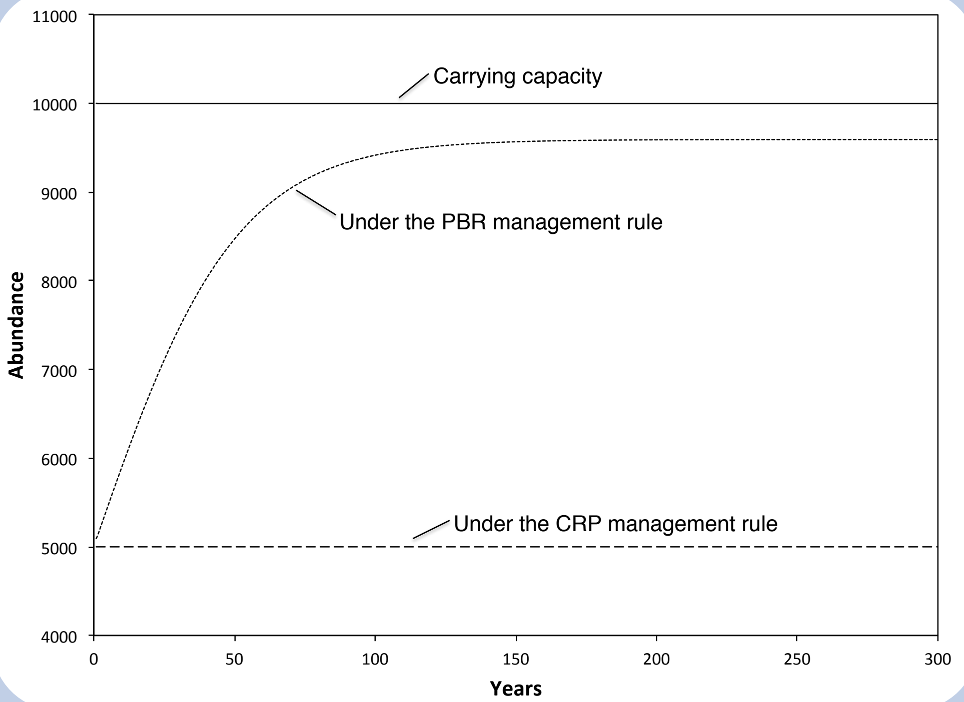
sperm whales (Annex 6; Taylor et al., 1997); and $R_{max,i}$ the maximum theoretical growth rate for the sub-population *i*, defined respectively at 0.04 and 0.03 for the fin and sperm whales (standard reference parameters from Taylor et al., 2007).

The CRP represents the maximum number of animals, not including natural mortalities, that can be removed without triggering a decrease in the population trend (Caswell et al., 1998). This management rule is often defined as a default rule when no others are available (IWC, 1996, 1991), and the ACCOBAMS implicitly advocates for the CRP in their guidelines (ACCOBAMS, 2016). According to Caswell et al. (1998), the CRP is calculated as follows:

$$CRP_i = {}^{1}/_{2}\, R_{max,i} \qquad (5)$$

Box. 1: Management rule targets

The Potential Biological Removal (PBR) and the Critical Reference Point (CRP) respectively correspond to the most and the least conservative management rules in the literature. As theoretically illustrated in Box-Fig. 1, a population under the PBR management rule will recover to between 70% and 95% of its carrying-capacity within 100 years (Wade, 1998), whereas a population under the CRP management rule remains stable.



Box-Figure 1. Evolution of the abundance of a theoretical population under the Potential Biological Removal management rule (dotted curve) and a population under the Critical Reference Point management rule (dashed curve). The population starts here with a theoretical initial population of 5,000 individuals and has a carrying-capacity of 10,000 individuals (black line). Conception: Sèbe.

Estimating the consequences

The severity of the HIDM on the sub-populations is calculated using the HIDM/PBR and HIDM/CRP ratios. These ratios indicate how far the number of HIDM is from the target number informed by management rules. It is important to note, that these ratios are independent of the abundance estimates (see Annex 6 for more detailed information).

Literature review

In order to take into account uncertainty on biological parameters, a literature review was performed to gather several estimations of abundance and survival rates on fin and sperm whales (see Annex 6 for further information).

3. RESULTS

3.1. DATA COLLECTION

Our analysis of the MEDACES database suggests that an average of 7.1 (*SE*=1.3) fin whales and 9.3 (*SE*=1.7) sperm whales strand on the Mediterranean coasts each year (based on data from 2005 to 2015). The proportion of mortality not related to HIDM amongst these strandings, here labelled as "natural mortality"[33], varies by country MSN. French, Italian, and Greek MSNs shared the causes of mortality reported in their strandings (Tab. 11). Amongst the HIDM in the stranding data, entanglements result in more mortality than collisions for sperm whales, whereas collisions appear to be the primary cause of death in fin whales (see collision/entanglement ratios in Tab. 11).

Table 11. Summary of the French, Greek, and Italian MSN databases.

Species	Stranging network country	Total number of strandings (deaths)	Period	% of HIDM (collision/ entanglement ratio)	% of death of unknown causes – here defined as natural mortality.	Sources
Sperm whale	France	35	1980-2017	22.9 (0.75)	77.1	Observatoire PELAGIS – UMS 3462 (Université de La Rochelle – CNRS)
	Greece	28	1992-2014	42.9 (n.s)	57.1	Frantzis, Leaper, Paraskevi, & Lekkas (2015)
	Italy	192	1986-2018	35.9 (0.07)	64.1	Università degli Studi di Pavia
Fin whale	France	82	1980-2017	26.8 (9.5)	73.1	Observatoire PELAGIS – UMS 3462 (Université de La Rochelle – CNRS)
	Greece	5	2000-2018	40 (2:0)	60	Frantzis pers. comm., unpublished data of Pelagos Cetacean Research Institute
	Italy	93	1986-2018	20.4 (3.75)	79.6	Università degli Studi di Pavia

[33] This assumption is discussed in the section 4.

As there is heterogeneity regarding the natural mortality proportions in strandings (Tab. 11), we took into account this uncertainty factor by expressing the HIDM results of this study using three scenarios: lowest, average and highest percentages of natural mortality in the MSN database. These percentages correspond, respectively, to 60%, 73% and 80% for fin whales and to 57%, 64% and 77% for sperm whales.

Another uncertainty within the variables used lies with the abundance data, as few studies have estimated this variable for the Mediterranean sub-populations (Annex 6). Thus, we took this uncertainty factor into account by expressing the HIDM results according to abundance values included in the range of possibilities in the literature. In addition, after reviewing the literature, we used the most probable values as an illustration for this paper: 2,500 individuals (*CI:* 1,472-4,310) for the Mediterranean fin whale sub-population (Laran et al., 2017), and 1,842 individuals[34] for the sperm whale sub-population (Lewis et al.,2018).

3.2. SEVERITY OF THE HIDM IMPACT ON WHALES

Table 12 shows our estimations of HIDM, carcass recovery rates, PBR, CRP, HIDM/PBR and HIDM/CRP ratios, given the most probable abundance number in the literature (i.e., Laran et al., 2017 for fin whales ; Lewis et al., 2018 for sperm whales) and according to the three selected scenarios of natural mortalities in strandings (lowest, average and highest values in MSN databases). Figure 23 displays the total annual number of HIDM for sperm and fin whales depending on sub-population abundances (based on range of possibilities in the literature), and accounting for uncertainties in the percentage of natural mortality identified in the stranding data.

The total annual HIDM for the Mediterranean fin whale ranges from 8.2x above the PBR to 0.8x below the CRP, regardless of the abundance, and given the average percentage of natural mortality in strandings (Tab. 12). For the sperm whales, the number of HIDM ranges from 4.8x above the PBR to 0.5x below the CRP, with the average percentage of natural mortality in stranding scenario and regardless of the abundance (Tab. 12).

While the number of HIDM for the sperm whale is always below the CRP regardless of the selected percentage of natural mortality in strandings, for the fin whales, it could be up to 1.3x higher than the CRP in the less conservative configuration (i.e., 60% of natural mortality in strandings; upper boundary of the blue area in Figure 23; Table 12).

[34] No measure of variance available as the calculation was done from a single acoustics transect.

Table 12. Estimations of HIDM, carcass recovery rates, PBR, CRP, HIDM/PBR and HIDM/CRP ratios depending on the three selected scenarios of natural mortalities in strandings (MSN), based on the most probable abundance in the literature: 1,842 individuals for sperm whales (Lewis et al., 2018) and of 2,500 individuals for fin whales (Laran et al., 2017). The HIDM/PBR and HIDM/CRP ratios are indicators to the respect of the management rules. If the HIDM/PBR and the HIDM/CRP ratios are superior to 1, the number of HIDM is higher than the respective management rule by the ratio indicated (in red). Similarly, if the HIDM/PBR and the HIDM/CRP ratios are inferior to 1, the number of HIDM is lower than the respective management rule by the ratio indicated (in green).

Species	Scenario	HIDM (ind/yr)	Carcass recovery rate (%)	PBR (ind/yr)	HIDM /PBR ratio	CRP (ind/yr)	HIDM /PBR ratio
Fin whale	Lowest % of natural mortality in strandings (60%)	66.7	4.3	5	13.2	50	1.3
	Average % of natural mortality in strandings (71%)	40.8	5.0	5	8.2	50	0.8
	Highest % of natural mortality in strandings (80%)	25	5.7	5	5.0	50	0.5
Sperm whale	Lowest % of natural mortality in strandings (57%)	19.5	20.6	2,8	7.0	28	0.7
	Average % of natural mortality in strandings (66%)	13.3	23.8	2,8	4.8	28	0.5
	Highest % of natural mortality in strandings (77%)	6.4	27.8	2,8	2.3	28	0.2

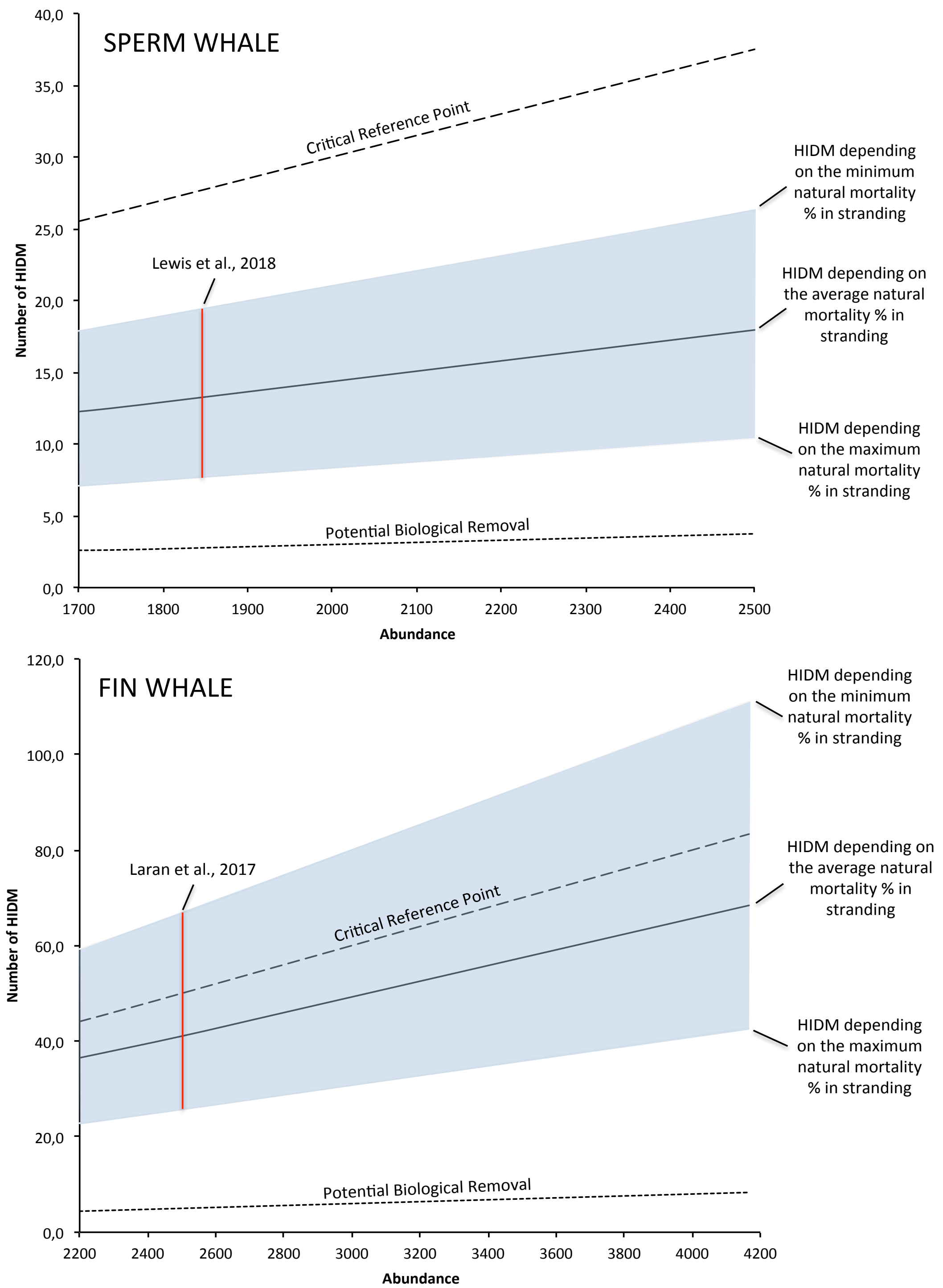


Figure 23. Number of annual total HIDM in sperm (top) and fin (bottom) whale sub-populations according to sub-population abundance. The blue area represents the range of possibilities of total HIDM estimated based on the minimum and maximum percentages of natural mortality in the MSN databases. The black line represents the total number of HIDM per year based on the average percentage of natural mortality in the MSN databases. The dotted and dashed lines correspond respectively to the PBR and the CRP estimations. The red vertical lines correspond to the total HIDM depending on the most probable abundance value used (Laran et al., 2017; Lewis et al., 2018). Conception: Authors.

Box. 2: Number of collisions

Refined assessments of causes of mortality from the stranding networks would improve our knowledge and would allow a more accurate estimation of the number of collisions in the Mediterranean. Currently, collisions represent, on average, $p_1 = 25\%$ and $p_2 = 83.7\%$ of the causes of mortality in the Mediterranean stranding data (MSN), respectively for sperm and fin whales. Using the Vanderlaan and Taggart (2007) approach, updated by Conn and Silber (2013), the probability of a lethal injury from a collision P_{lethal} is determined as follows: $P_{lethal} = \frac{1}{1+e^{-(\beta_0+\beta_1 V_S)}}$ where β_0 = -1.905 and β_1 = 0.217 (Conn and Silber, 2013); and Vs, the average ship speed in the Mediterranean is equal to 14.05kn (ENVIGIS software).

We estimate here the annual number of collisions (n_{col}) by taking average parameters and abundance estimates from Laran et al. (2017) and Lewis et al. (2018). n_{col} is calculated as follows: $n_{col} = M_{HIDM_{col}}(1 + e^{-(-1.905+0.217\,V_S)})$ where $M_{HIDM_{col}}$ is the number of HIDM due to collisions. $M_{HIDM_{col}}$ is extrapolated by applying the percentage of mortality due to collisions in the stranding data (p_1 and p_2) to the total number of estimated HIDM (M_{HIDM}). As a result, given the parameters chosen as an illustration in this chapter, the number of collisions per year in the Mediterranean is estimated to **45 col/y** and **15 col/y**, respectively, for fin and sperm whales. Further research is required to reduce the uncertainty of the approach.

4. DISCUSSION

The enclosed nature of the Mediterranean basin is an excellent framework for assessing the severity of HIDM on the Mediterranean fin and sperm whale sub-populations. Ratios of HIDM by management rules provides a snapshot of the current state of the Mediterranean sub-population, and on the conservation perspectives.

4.1. IMPLICATION FOR SUB-POPULATION STATUS

Our results confirm that the IUCN status of the Mediterranean fin whale sub-population should be reassessed, as stated in recent literature (Notarbartolo di Sciara et al., 2016). The number of HIDM is consistently greater than the Potential Biological Removal (PBR; most conservative management rule) and is close to the Critical Reference Point (CRP; less conservative management rule), even exceeding it in some cases, regardless of the parameter values used (Tab. 12). This suggests that collisions and entanglements alone are responsible for the decrease in abundance of the fin whale sub-population. This decrease has been suggested in the recent literature. Amongst others, Notarbartolo di Sciara et al. (2016) estimated a 60% decrease in fin whale sightings during population estimates transect between 1992 and 2011. Our results, therefore, confirm and quantify the impact of the HIDM on this sub-population (Notarbartolo di Sciara, 2016; Panigada et al., 2008, 2006). David et al. (2011) have assessed that each year, 210 fin whale individuals are at risk of collision in the Pelagos Sanctuary and adjacent waters in the summer. They estimated more specifically, that an average of 3.4 individuals/day could be in the path of any large ship in the Pelagos Sanctuary. Panigada et al. (2006) assessed the number of deadly collisions to be between 6.9 and 40.11 individuals/year in this MPA. Our study used the most probable abundance estimate of 2,500 individuals (ICMMPA, 2019; Laran et al., 2017), and assessed the number of HIDMs, collisions and entanglements, between 25 and 67 individuals/year for the entirety of the Mediterranean Sea (Tab. 12).

The Mediterranean sperm whale sub-population is less impacted by HIDM than the fin whales. Our estimations show that HIDM never pushes the mortality above the CRP on its own, regardless of the range of parameter values used in this study. Our calculations show that collisions and entanglements are not solely responsible for the decreasing abundance trend (David et al., 2018; Frantzis et al., 2019). Nonetheless, David et al. (2018) estimated that 74 sperm whales were potentially in the large commercial ship paths in the Pelagos Sanctuary region during the summer of 2010. In Greece, several deadly collisions occur each year (Rendell and Frantzis, 2016). Our study used the most probable abundance estimate of 2,500 individuals (ICMMPA, 2019; Lewis et al., 2018), and assessed the number of mortalities due to collision and entanglement to be between 6 and 19 individuals/year within the entire Mediterranean (Tab. 12).

The Mediterranean sub-populations are also threatened by HIIM. Besides collisions, maritime transport generates sounds that mask communication between whales using low frequencies, such as fin whales (Southall et al., 2007). This masking is known to disturb feeding, communication, and migration (Thomas et al., 2016), leading to a lower survival rate (Notarbartolo di Sciara et al., 2016). Studies showed a significant reduction in whale sightings in favorable Mediterranean fin whale habitats, probably due to high ship traffic density (Vaes and Druon, 2013). Castellote et al. (2012) also observed a change in fin whale acoustic patterns in high traffic density areas. The fin whale sub-population is also under threat from pollution, in particular from micro-plastics (Fossi et al., 2014, 2012). The carcass recovery rate values can give insigths into the level of HIIM for the Mediterranean fin whales. The carcass recovery rate for fin whales is estimated here between 4.26% and 5.65%. No previously published estimates of carcass recovery for this species exist to the authors' knowledge. The only estimations of great whale carcass recovery rates are for grey and right whales (respectively estimated at 5% and 17%; Heyning and Dahlheim, 1990; Kraus, 2005). While it is challenging to compare different species, we can observe that the fin whale carcass recovery rate is within this expected range. As the carcass recovery rate is in the expected range, the theoretical survival rate ($s_{0,\text{fin whale}} = 0.96$) used in this study should be close to its actual value. The theoretical survival rate ($s_{0,\text{fin whale}} = 0.96$) used in this study does not account for HIDM and HIIM, which explains that observed survival rates are lower (between 0.88 and 0.94; Table 2; Notarbartolo di Sciara et al., 2016; Rossi et al., 2014). Consequently, given the survival rate calculation[35], and that, in our approach, HIIM is combined with the natural mortality; our results indicate that HIDM may be the main contributor to the mortality, and that the HIIM plays a lesser role.

HIIM seems to be more threatening than HIDM to the survival of the Mediterranean sperm whale sub-population. Similar to the fin whales, the carcass recovery rate can be used to interpret the contribution of the HIIM to the survival rate; the carcass recovery rate for sperm whales is between 20.6% and 27.8%. In the literature, Williams et al. (2011) estimated a rate of 3.4% for this species in the Gulf of México. The semi-enclosed characteristics of the Mediterranean basin cannot alone explain such a difference between our estimates and the ones from Williams et al. (2011). If we use the same assumptions as we did for fin whales, the high carcass recovery rate estimated in our study indicates a high contribution of HIIM to the survival rate. This high contribution of the HIIM is supported in the literature by several studies highlighting the sensitivity of the Mediterranean sperm whale sub-population to these threats. The high seismic survey activity in the region may play an indirect role in stranding events (Mazzariol et al., 2011). This activity might also be partly responsible for prey depletion (e.g., cephalopods), contributing to some stranded carcasses showing signs consistent with starvation (Mazzariol et al., 2011; Notarbartolo-Di-Sciara, 2014; Roberts, 2003). The ingestion of debris is also a cause of concern (Mazzariol et al., 2011; Notarbartolo-Di-Sciara, 2014), as it might lead to lower survival probabilities (Pace et al., 2015; Simmonds, 2012). Chemical pollutants, especially persistent organic pollutants, are known to be present in high concentrations in Mediterranean sperm whale blubber, but the impact of these contaminations has not yet been quantified (Pinzone et al., 2015; Squadrone et al., 2015). Furthermore, this species seems particularly sensitive to climate change (Notarbartolo-Di-Sciara, 2014).

4.2. DEALING WITH UNCERTAINTY

The lack of data in the Mediterranean makes it challenging to assess precisely the impact of HIDM on the fin and sperm whale sub-populations (Mannocci et al., 2018). In order to overcome this lack of precision, we presented our results giving a range of uncertainty (e.g., Table 2, Figure 1). We also expressed our results providing the most probable estimates for each parameter used.

[35] The survival rate is expressed as follows: $s = 1 - m_n - m_{HIIM} - m_{HIDM}$, with s the survival rate, m_n the mortality rate due to natural mortality, m_{HIIM} the mortality rate due to HIIM, m_{HIDM} the mortality rate due to HIDM (Gilbert et al., 2017).

Stranding data

The stranding data are heterogeneous regarding the description of cause of death (Peltier et al., 2019). While death due to HIDM are described in the MSNs (e.g., collision, entanglement), other causes of mortality are labelled as *"unknown"*. An *"unknown"* cause of death can be given for various reasons, including carcasses that are too decomposed to accurately assess the cause of death and discrepancies in staff training can also be a factor (Worthy, 1999). The stranding events categorized as *"unknown"* can therefore, in reality, include cases where the whale died as a result of HIIM, natural causes, and also from HIDM that was not identified (Worthy, 1999). We assumed in our calculations that *"unknown"* causes of death are the result of natural mortality. This assumption could lead to an underestimation of the HIDM. We thus expressed the results as the minimum, maximum, and average percentages of natural mortality that can be found in the stranding databases (MSN) to account for the uncertainty surrounding the cause of death. The interpretation of the carcass recovery rate helped to give insights into the implications of HIDM and HIIM as described in the previous sub-section.

Abundance

As an illustration for this Chapter, we choose to use the value of 2,500 individuals for fin whales as it is the most probable value given the existing literature (Laran et al., 2017). There is no agreed estimate for Mediterranean whale abundance in the literature (Annex 6). Regarding fin whales, some studies only estimated the number of individuals in restricted regions of the Mediterranean Sea (Arcangeli et al., 2017; Panigada et al., 2017, 2011). On a larger scale, Laran et al. (2017) estimated an abundance of 2,500 individuals (*CI:* 1,472-4,310) in the Northwestern region of the Mediterranean during the summer period, which represents the annual peak of abundance in the region. Forcada et al. (1996) assessed an abundance of 3,583 individuals (*CV*=0.27) in the Mediterranean Western basin. However, recent studies suggest this number might include seasonally migrating individuals from the Atlantic population (Notarbartolo di Sciara et al., 2016). The IUCN assessment indicated that there are less than 5,000 individuals throughout the Mediterranean basin (Panigada and di Sciara, 2012). This number is far more optimistic than the primary results of the ACCOBAMS Survey Initiative (ASI), which are scheduled to be confirmed in the coming months. They estimate the total abundance of the Mediterranean fin whale sub-population to be ca. 2,500 individuals (unpublished results presented at the ICMMPA, 2019).

As with fin whales, we chose to use the most probable value of 1,842 individuals for sperm whales for the calculations in this paper (Lewis et al., 2018). Abundance estimates for the Mediterranean sperm whale sub-population are scarcer. Apart from a local study (Arcangeli et al., 2017), two larger scale assessments were made. First, Laran et al. (2017) estimated an abundance of 565 individuals (*CI:* 123-2,653) in the Northwestern region of the Mediterranean during the winter period, which represents the annual peak in abundance in the region. Second, for the Mediterranean basin as a whole, Lewis et al. (2018) used a single acoustics transect to estimate an abundance of 1,842 individuals (no measure of variance available). The IUCN assessment indicates a sub-population inferior to 2,500 mature individuals (Drouot et al., 2004; Notarbartolo di Sciara et al., 2012). Primary results of the ASI estimates ca. 1,500 individuals in the Mediterranean basin (unpublished results presented at the ICMMPA, 2019).

Survival rate

While some estimates are available for fin whales (Notarbartolo di Sciara et al., 2016; Rossi et al., 2014), the lack of knowledge on the survival parameters of sperm whales prevents a robust interpretation of the high carcass recovery rate. The high recovery rate estimated here is probably due to a combination of a high proportion of HIIM and of the semi-enclosed basin, which increases carcass recovery. The combination of these two factors makes it challenging to quantify the sperm whale survival rate without estimations.

4.3. CONSERVATION IMPLICATIONS

A thorough risk analysis gives added value to the decision process for the implementation of conservation measures (Carwardine et al., 2008; Claudet and Fraschetti, 2010; IMO, 2018a; Vanem, 2012). Without knowing of the level of risk, decision-making can be hampered by such things as a lack of government enforcement of a measure, or the unwillingness of the stakeholders to act (Gok and Atsan, 2016; Kirchler et al., 2008; Sèbe et al., 2019). The unique characteristics of the Mediterranean enables us to estimate the severity of HIDM impact in a data-poor environment.

The contribution of HIDMs, especially collisions, to the total mortality induced by human activitiy (HIDM and HIIM) is high for fin whales. In contrast, HIDM does not appear to be the main contributor to sperm whale human-induced mortality, despite a high contribution of entanglement at the Mediterranean scale, so for sperm whales, conservation efforts should be focused on HIIM.

At the local level, pressure should be maintained to mitigate the impact of collisions and entanglement in identified hot spots. Despite the relatively low incidence of HIDM on sperm whales, local initiatives can help lower the mortality. Existing initiatives should be strengthened in the identified sperm whales collision hot spot in the Hellenic trench (Frantzis et al., 2019), and to a lesser extent, in the Pelagos sanctuary (David et al., 2018). The threat related to entanglement is mainly due to illegal fishing,now that driftnets have been banned by the international communityand regulatory bodie. This makes it difficult for conservationists to take or propose actions that are not enforced and so it remains more of a police matter to control illegal fishing (Notarbartolo-Di-Sciara, 2014; UNEP, 2015). For fin whales, it is crucial to deal with the collision issue, which our data suggests is highly responsible for the decrease in abundance of this species in the region. The hot spot of collisions identified in the Northwestern part of the Mediterranean requires stricter rules and the development of enforcement measures. In addition, the project to expand the boundaries of the Pelagos Sanctuary to include most of the fin whale coastal summer habitat should be encouraged (Laran et al., 2017; Notarbartolo di Sciara et al., 2016). More generally, governments of the Mediterranean countries should implement mitigation solutions, similar to those which have been imposed by the French government. A law was passed, making it compulsory for all French ships to have a device installed that shares the position of whale sightings within the Pelagos Sanctuary (République Française, 2016). Other measures should be implemented, such as areas to be avoided, speed restrictions, or dedicated observers (Freedman et al., 2017; Vanderlaan and Taggart, 2009; Weinrich et al., 2010). Inter-country proposals to the IMO could also strengthen local actions (Geijer and Jones, 2015; ICMMPA, 2019).

At the regional and international level, the ACCOBAMS implicitly advocates for the CRP, the least conservative management rule. In their guidelines, the ACCOBAMS advocates for removals below 2% of the sub-population (ACCOBAMS, 2016), which corresponds to half of the survival rate (i.e., CRP calculation), based on the original calculation (IWC, 1996, 1991)[36]. We advocate that the ACCOBAMS should revise its recommendation, especially for fin whales, towards the implementation of stricter management rules similar to those which were applied in the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and

[36] The ACCOBAMS *"threshold of 2% of the total population"* guideline (ACCOBAMS, 2016) is based on the book of Perrin et al., (1994). When studying this book, we trace back this guideline to the IWC report (1991) which states that the original calculation of this threshold corresponds to half the survival rate multiply by the abundance, aka the CRP calculation ($1/2\ R_{max,i}$; IWC, 1991).

North Seas (ASCOBANS; Reeves and Brownell, 2009). The ASCOBANS implemented a management rule for a population of harbor porpoises where the death due to HIDM wasinferior to 1% of individuals, which is equivalent to a quarter of the survival rate ($^1/_4\, R_{max,i}$; Caswell et al., 1998; Reeves and Brownell, 2009). The aim was to establish a threshold that would trigger immediate actions when breached, and prevent the decision-makers from using the uncertainty of HIDM estimations as an excuse not to act. As an illustration, our study shows that the number of HIDM for Mediterranean fin whales is close to the CRP, and even exceeds it when considering the scenario of the lowest percentage of natural mortality in strandings. The level of uncertainty surrounding the severity of threats to whales has been used in the past by industries and governements to justify inaction (World Shipping Council, 2006). The estimated number of HIDMs for fin whales in our study would be equal or even surpass this rule if a management rule equivalent to the one implemented by ASCOBANS (1%) was fixed as an *"intermediate precautionary objective"* (ASCOBANS, 2000). This would set a more ambitious threshold given the actual uncertainty, and encourage decision-makers to recommend and use mitigation solutions. For sperm whales, the ACCOBAMS should strengthen the Thematic 6 of its strategy, which aims to improving the knowledge of the survival rate and reproductive success of marine mammals, and equally a better understanding of the HIIM threats (ACCOBAMS, 2019). Our calculated level of HIDM is far higher than the PBR for both sub-populations; the Marine Mammal Protection Act requires implementing a plan to lower the HIDM below the PBR within 6 months when HIDM levels exceed PBR in the U.S. (Geijer and Read, 2013; Moore et al., 2009). This fact highlights the precarious state of Mediterranean fin and sperm whale sub-populations.

The IUCN should revise the endangerment status of the Mediterranean fin whale population to a more threatened category, as recently advocated in the literature (Notarbartolo di Sciara et al., 2016). This revision would be decisive for decision-makers, and may strengthen the protection of identified areas of interest such as Ecologically or Biologically Significant Areas (EBSA from the Convention on the Biological Diversity), the Key Biodiversity Areas (KBA from the IUCN), or the recently developed Important Marine Mammal Areas (IMMA from the ICMMPA) (Corrigan et al., 2014). However, despite the significance of decisions being made in these areas, the subsequent lack of enforcement remains problematic (Báez et al., 2019). Similarly to these areas and to ACCOBAMS, this absence of enforcement can also be found within the International Whaling Commission (IWC; Mazzanti, 2001), the long-standing organization dealing with whale matters at the international level (Wright et al., 2016). A more regulatory framework should be implemented for managing whale human-induced mortality, at least for HIDMs (Geijer and Jones, 2015; Sèbe et al., 2019; G. K. Silber et al., 2012).

For collisions, Geijer and Jones (2015) observed that the International Maritime Organization (IMO) holds key features to enforce collision mitigation solutions. Other studies have highlighted the advantages of a potential involvement of the IMO for the management of shipping-related threats to whales (Sèbe et al., 2019, 2020; G. K. Silber et al., 2012). This involvement historically led to better compliance of the shipping industry with solutions through mandatory requirements (e.g., Lagueux et al., 2011; McKenna et al., 2012). The IMO involvement also allows decreasing the loss of competitiveness between the shipping companies (Anonymous, 2019). For instance, the French law on the device that shares the position of whale sightings is only mandatory for French ships crossing the Pelagos Sanctuary (République Française, 2016); an IMO ruling would also require foreign flag ships to use identical equipment when passing through this zone, thus removing competitiveness between French and foreign ships (Gritsenko and Yliskylä-Peuralaht, 2013; ICMMPA, 2019; Stopford, 2009). Several ways exist to implement mandatory measures at the IMO level, such as: (1) proposing mitigation solutions to the Marine Environment Protection Committee (MEPC; e.g., IMO, 2007); (2) proposing a Particularly Sensitive Seas Areas (PSSA; IMO, 2016, 2006), in which the implementation of risk reduction measures are possible; (3) proposing a possible involvement in the Mediterranean Emission Control Area (ECA) potential designation (Redfern et al., 2019), to propose the implementation of speed reduction measures within collision hot spots; and (4) proposing solutions through the IMO risk assessment framework, namely the Formal Safety Assessment (FSA; Sèbe et al., 2019).

Other organizations could become involved to propose similar initiatives to mitigate enganglements. These organizations include the Food and Agriculture Organization (FAO), the IMO counterpart for fishing (FAO, 2004), the European Commission, the International Commission for the Conservation of Atlantic Tuna, the General Fisheries Commission for the Mediterranean, and the CMS Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea, and Contiguous Atlantic Area (Notarbartolo-Di-Sciara, 2014).

There are many ways to achieve a more regulatory framework. Central to all decision-making is defining the risk-level at the population scale, as it conveys the notion of acceptable risk. The acceptable risk corresponds *to "the level of human, property [, or environmental] loss that can be tolerated by an individual, household, group, organization, community, region, state, or nation"* (Svalova, 2018). By using here HIDM/PBR and HIDM/CRP ratios, we give insight into the notion of unacceptable risk (HIDM/CRP>1), acceptable risk (HIDM/CRP<1 combined with HIDM/PBR>1), and negligible risk (HIDM/PBR<1). This notion is crucial for the transparency of the decision process, and has been implicitly used for several years in determining thresholds for fisheries, through, for example, Ecological Risk Assessment (Hobday et al., 2011; Smith et al., 2007)

4.4. FUTURE RESEARCH

Further research will help to improve whale survival in the Mediterranean sea. Different MSNs are more or less well organized (Pace et al., 2015); improvements have recently been made, and should be continued for identifying deaths due to collisions in strandings. Continued cooperation between all the Mediterranean countries needs to be encouragd to building capacity of the less operational MSNs (ACCOBAMS-ECS, 2018). A common operational stranding protocol would improve the identification of the cause of death and refine the results of the carcass recovery rate approach. Recent studies have improved the identification of collision-related deaths (Arregui et al., 2019). The improvement of HIDM identification in strandings may help to separate the HIDM specific mortality rate from that of HIIM and natural mortality (Gilbert et al., 2017). As it stands, it is difficult to differentiate between death due to HIIM and death by natural causes.

A definition of the carcass recovery rate based on models of the pattern of water circulation within the Mediterranean would be useful to refine the results (Peltier et al., 2016; Peltier and Ridoux, 2015). The carcass recovery used in this study is based on the theoretical natural mortality of each sub-population. Modeling the currents coupled with a buoyancy study of each species (Couvat et al., 2016; Peltier et al., 2016) would enable more direct estimations of the carcass recovery rates, which would reduce the uncertainty of the HIDM results presented in this study.

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CHAPTER 5

Risk Evaluation Criterion: Evaluation of Measures to Reduce Ship Strikes – A Mediterranean Case Study

"Ecologists and economists made unlikely partners – indeed, these disciplines have often appeared at odds with, and determined to ignore each other...."

M. Sagoff, 2012

Recommended citation:

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FOREWORD

This chapter is exploratory, and gives first insights on the definition of a *"whale"* risk evaluation criterion. This work may be continued after the thesis in order to overcome its identified limitations. Besides, this work would require a reorganization to be submitted as a research article, and reach a broader audience.

ABSTRACT

The collisions between ships and whales can represent a significant threat to some whale populations' survival. The lack of robust and holistic assessments of the consequences of the mitigation solutions on the shipping industry often leads to low compliance from this industry. To overcome this lack of compliance, several voices arose for a more regulatory approach of the whale-ship collision management, through the International Maritime Organization. Within this organization, discussions emerged for the definition of risk evaluation criteria for environmental issues to compare the costs of implementing mitigation solutions to the benefits induced by them. These criteria can then be used within these solutions cost-benefit and cost-effectiveness analyses to help decision-makers recommendations. To define this risk evaluation criterion for whales, we used an ecological-economic framework based on the existence value and on conservation targets – management rules. As an illustration, we applied our framework to the Mediterranean fin whale population, and found a risk evaluation criterion – cost of averting a whale fatality – of US$562,462 (US$2017). When applied to our case study, and if the IMO were to adopt on our risk evaluation criterion, the mitigation solution monetized in the literature would be recommended. The setting of an effective risk evaluation criterion might increase the number of pro-whale measures approved at the IMO level, as it would increase the transparency of the proposals. With time, the IMO recommended solutions would increase the compliance from the shipping companies with the mitigation solutions, and, therefore, improve whale conservation.

Keywords: whale-ship collision, risk evaluation criterion, Formal Safety Assessment, cost of averting a whale fatality, cost-effectiveness analyses.

1. INTRODUCTION

Collisions between ships and whales are a major threat to some populations' survival (Ritter and Panigada, 2019). Several collision *"hot spots"* have been identified (Avila et al., 2018; Cates et al., 2016), in which the levels of pressure are usually defined as inadequate for the resident populations' survival (Rendell and Frantzis, 2016). Often deadly, the origin of this threat lies in the overlap between whale habitats and maritime roads (Dransfield et al., 2014). Furthermore, the increase of marine traffic and the speed capabilities of the new generation of ships will intensify the collision threat in the coming years (Pirotta et al., 2018; G. K. Silber et al., 2012; Vanderlaan and Taggart, 2007).

Several solutions have been proposed to mitigate the impact of collisions. On one hand, operational solutions, such as speed reduction or avoidance of whale high-density areas, are known to be the most effective solutions (Vanderlaan et al., 2009; Vanderlaan and Taggart, 2009). On the other hand, technical solutions, such as detection tools, have been tested, but have rarely met expectations (Silber et al., 2008a).

Compliance from the shipping industry with mitigation solutions – whether operational or technical – is often limited (Chion et al., 2018a; Freedman et al., 2017). The lack of robust assessments has been highlighted as a contributing factor to the shipping industry's low compliance (Firestone et al., 2008; World Shipping Council, 2006). Low compliance leads to low applied effectiveness, despite the high theoretical effectiveness of the proposed solutions. In the case of whale-ship collisions, the effectiveness of a mitigation measure is rarely put in perspective with the costs and benefits associated with it. This lack of a holistic view impedes decision-makers' recommendation, government enforcement, or industries' willingness to act (Sèbe et al., 2019, 2020).

Recently, the application of a risk assessment framework introduced by the International Maritime Organization (IMO), namely the Formal Safety Assessment (FSA), has been conceptualized for the case of whale-ship collisions to overcome this lack holistic approach (Sèbe et al., 2019). The IMO, the United Nations organization responsible for regulating shipping, introduced FSA as *"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"* (IMO, 2018a). Addressing environmental issues through the use of FSA is relatively recent (Kontovas and Psaraftis, 2009; Sèbe et al., 2019).

The FSA follows the rationale of risk assessment techniques and recommends a five-step approach, consisting of Hazard Identification (Step1), Risk Assessment (Step2), proposing mitigation solutions – Risk Control Option (RCO) in the FSA terminology – (Step 3), performing a Cost-Benefit assessment (Step 4) and, finally providing recommendations for decision making (Step 5). The penultimate step (i.e., Cost-Benefit assessment) is probably the most important given that possible recommendations of decision-makers will be based on this analysis. This step aims to identify and compare the benefits and costs associated with the implementation of a mitigation solution. The definition of this step in the FSA guidelines is quite fuzzy, and has been subject to several discussions in the literature (Kontovas and Psaraftis, 2009; Zheng, 2006). While Step 4 is entitled *"Cost-Benefit assessment"*, in practice, the FSA guidelines describe a Cost-Effectiveness assessment (CEA). Also, according to the FSA guidelines, mainly private costs and benefits can be integrated (Huysegoms et al., 2018; Zheng, 2006). For example, only the ships' avoided costs – and to lesser extent carcasses' management – would be eligible for this analysis in the case of whale-ship collisions (Couvat et al., 2016; Mayol, 2012; Sèbe et al., 2020; Van Waerebeek and Leaper, 2008).

However, the FSA has provisions for risk evaluation criteria to integrate indirectly the potential social benefits into its analysis (e.g., saving a whale). Several discussions emerged for the definition of risk evaluation criteria for environmental issues to compare the costs of implementing mitigation solutions to the benefits induced by them (Kontovas et al., 2010; Psaraftis, 2008). Risk evaluation criteria are useful tools for decision-making as they *"define how risks are measured (metric), the level of risks that are acceptable and the level of investment in risk reduction that are deemed necessary"* (Skjong et al., 2005). These criteria can be used within these solutions' cost-benefit or cost-effectiveness analyses to help decision-makers recommendations. The Formal Safety Assessment (FSA) guidelines indicate possible methodologies to evaluate such criteria:

- (a) Observations of the willingness to pay to avert a fatality;
- (b) Observations of past decisions and the costs involved with them; and
- (c) Consideration of societal indicators.

Risk evaluation criteria have been defined for human health, oil spills, and proposed for gas emission (IMO, 2004b; Kontovas et al., 2010; Vanem, 2012). Following the same rationale, this exploratory Chapter aims to define such an evaluation criterion – through the cost of averting a whale fatality – for whale-related mitigation solutions by using the first methodology (a). Section 2 of this Chapter defines the calculation framework of the cost of averting a whale fatality (2.2) based on the value of protecting a whale population (2.1). Section 2.3 highlights the application of this framework to the Mediterranean fin whale – our case study –, and Section 2.4 shows the results of this application. Section 3 discusses the use of the cost of averting a whale fatality as a risk evaluation criterion within the FSA context. Section 4 discusses of the approach limitations. Finally, the last section concludes and proposes further researches on the subject.

2. VALUING THE BENEFIT OF REDUCING WHALE-SHIP COLLISION RISK

2.1. THE VALUE OF PROTECTING WHALES

Methods to define the value of a single whale or a whale population are numerous in the literature. Mainly, these studies use contingent valuation methods to assess the unitary willingness to pay (WTP) of people to conserve a whale population (Lew, 2015), and apply this WTP to the number of people in the study site (Bosetti and Pearce, 2003; Loomis, 2006). However, because contingent valuation methods are time-consuming and expensive, benefit transfer studies emerged to overcome these limitations (Amuakwa-Mensah, 2018; Richardson and Loomis, 2008). Benefit transfer is a methodology used to estimate the non-market value of a species in a locality of interest, depending on this value in one or several other study sites (U.S. EPA, 2014). Of course, the estimations done with the benefit transfer method is less accurate than with original studies (e.g. contingent valuation, travel cost), as the original studies are not tailored to the policy site.

For defining the cost of averting a whale fatality, we need first to define the value of protecting a whale population. This value is derived from the WTP per person – or household – to protect a whale population, either through contingent valuation or benefit transfer. The application of the unitary WTP per person – or household – to the inhabitants of the policy site to calculate the value of protecting an animal population is often debated in the literature. For endangered species, some authors apply the unitary WTP to all the inhabitants of the policy site – whatever the size of the site (e.g., country or larger area; Beaumont et al., 2008; Wakamatsu et al., 2018). Indeed, Wallmo and Lew (2015) did not identify a significant difference in the WTP value for endangered species between the policy site scope and the national scope. In other words, the WTP of a person near the policy site is the same as someone away from this policy site. However, to bound our study, we choose to use a distance-decay relationship to calculate the value of protecting a whale population (Bateman et al., 2006; Loomis, 2000) as follows:

$$V = v \times nb \times \gamma \qquad (1)$$

where, V is the value of protecting the whale population; v is the WTP to protect the whale population estimated per person – or household –; nb is the number of inhabitants – or households – in the policy site; and γ is the Loomis (2000) WTP distance-decay relationship (Fig. 24).

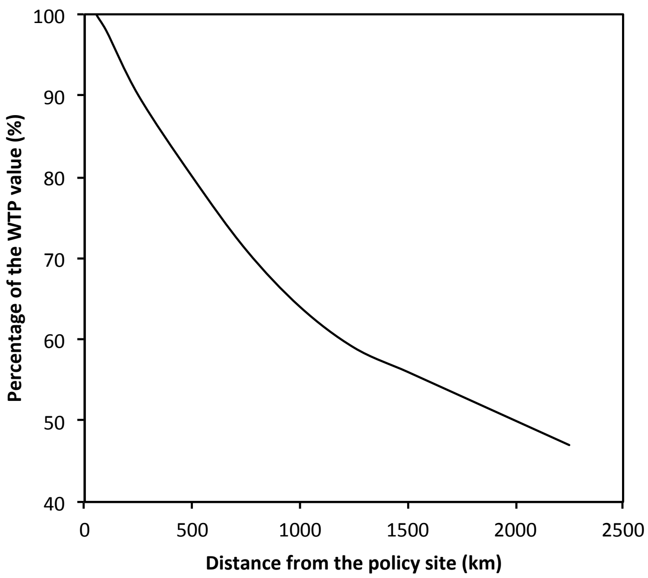

Figure 24. Loomis (2000) WTP distance-decay relationship for threatened and endangered species. Conception: Sèbe.

While the calculation of V using Equation 1 is somewhat straightforward, the definition of a function of V depending on the abundance is required to assess changes in this value due to whale individuals' mortality. Indeed, most of the contingent valuations – and the related benefit transfer functions – are based on the endangerment status, and not on the abundance of the population as the lack of data often hinder the use of this latter parameter.

Consequently, we use the behaviors of the WTP values depending on the endangerment status and the abundance described in the literature to build this function. Three WTP behaviors are used in our approach. First, the unitary willingness to pay v – and, therefore, the population value V -– increases when the endangerment status worsens; this decay in status is most likely due to a decrease in abundance[37] (Fig. 25a; Amuakwa-Mensah, 2018; IUCN, 2012; Martín-López et al., 2008; Richardson and Loomis, 2008). Second, the maximum willingness to pay $v_{\max}$ – and,

[37] Other factors contribute to changes in the endangerment status (e.g., reduction of habitat), but to simplify the approach, we choose to focus on the abundance factor. For more information on the other factors, the interested reader may refer to the IUCN guidelines (IUCN, 2012a).

therefore, the maximum population value V_{max} – can be related to the marginal WTP to conserve the last whale of the population (Gerber et al., 2014a). However, at one point, v will not increase, even if the state of the population keeps decreasing (choke price; Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008). Third, the minimum willingness to pay $v_{\min}$ – and, therefore, the minimum population value V_{min} – will never tend towards zero, because of the non-use value unrelated to the extinction. This is particularly true for charismatic species, which have a high existence value independently of their endangerment status (Bulte and Van Kooten, 1999; Colléony et al., 2017). In other word, when a population is close to its carrying-capacity K, the v_{min} and V_{min} will somewhat be high.

Thus, using these WTP behaviors, we derive a function of the population value depending on the abundance. As did Bulte and Van Kooten (1999), we assume that this function is linear to simplify our preliminary approach (Fig. 25b). With this assumption, we can define the equation of the linear function based on the two coordinates available based on the WTP behaviors expressed above: $(0; V_{max})$ and $(K; V_{min})$. Hence, the value of a protecting a population $\mathrm{V_{pop_t}}$ of abundance N_t, at the time t is calculated as follows (Fig. 25c):

$$V_t = \frac{(V_{min} - V_{max})}{K} \times N_t + V_{max} \qquad (2)$$

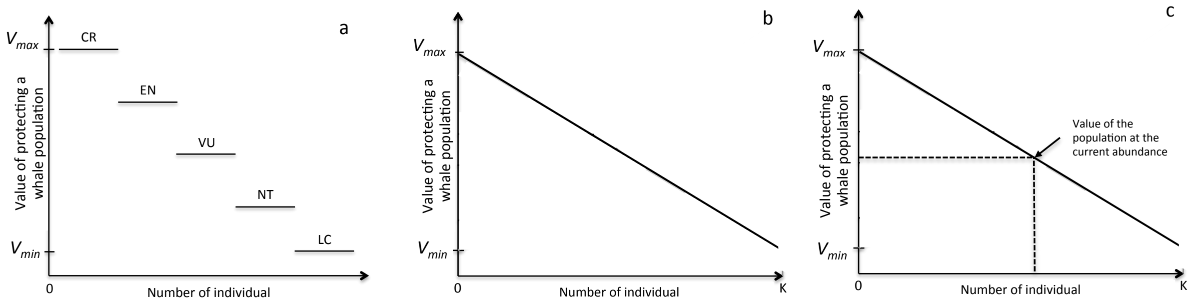

Figure 25. Conceptual illustration of the population value depending on the abundance. (a) represents the dependence between the population value and the endangerment status; (b) the linearity between the value and the abundance – assuming the link between the endangerment status and the abundance (Bulte and Van Kooten, 1999; IUCN, 2012a); (c) the calculation of the population value depending on the abundance at time *t*. IUCN status: CR = Critically endangered; EN = Endangered; VU = Vulnerable; NT= Near-threatened; LC = Least concern. K stands for carrying-capacity. Conception: Sèbe.

2.2. THE VALUE OF AVERTING A WHALE FATALITY

The main goal of this work is to examine the societal benefit of a whale – aka the cost of averting a whale fatality in the FSA terminology. Several studies have tried to derive the value of one whale (i.e., placing a monetary value on a whale life). For example, Knowles and Campbell (2011) attempted to estimate this value for whales in Australia using the total expenditure value of whale watching. Other studies have tried to assess the value of whales through a market approach in order to encourage conservation (Eiswerth and van Kooten, 2009; Gerber et al., 2014a), or rather the opposite, to promote whaling (Amundsen et al., 1995). Whatever the method, these estimations of the monetary value of a whale's life have often been criticized for ethical reasons (May, 1982). Notably, Babcock (2013) argues that whales have an intrinsic right to live; it is, therefore, amoral to put a monetary value on them. This ideology is built on the notion of moral values of biodiversity (e.g., pathocentrism: protecting species that can feel pain or pleasure; Wiegleb, 2002). In any case, in this preliminary study, we choose to explore this value to see its usefulness for whale conservation within the shipping industry's scope.

To define the cost of averting a whale fatality, we estimate the difference in theoretical value of protection between a population where a management rule is respected and a population where this management rule is not respected (Fig. 26). This difference converts the situation where the population's survival is not threatened by human activities vs. the one where it is threatened. Management rules, such as Limit Reference Points *"are removal thresholds to undesirable population or ecosystem states"* (Curtis et al., 2015). In our study, we use the most common management rule, the Potential Biological Removal (PBR). The PBR is *"the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population"* (Wade, 1998). It takes the form of $PBR = 0.5\, N_t\, r\, F_r$, where F_r is the recovery factor (Taylor et al., 1997); r is the intrinsic rate of increase (Taylor et al., 2007). Consequently, the cost of averting a whale fatality is calculated as follows:

$$\varphi_t = \frac{\Delta V_{t+1,i}}{\alpha_t} = \frac{\Delta V_{t+1,i}}{TR_t - PBR_t} \qquad (3)$$

where φ_t is the cost of averting a whale fatality; α_t is the difference between the total removals TR_t – not including natural mortalities – in the population and the removals *authorized* by the management rule PBR_t; $\Delta V_{t+1,i}$ is the difference in value between a population where the PBR_t is respected and a population where the PBR_t is not respected (TR_t). To calculate each value ($\Delta V_{t+1,i}$), we replace N_t by N_{t+1} in Equation 2. N_{t+1} is calculated using a marine mammal population dynamic model (Taylor & DeMaster, 1993), as follows:

$$N_{t+1} = N_t + r\, N_t \left[1 - \left(\frac{N_t}{K}\right)^{\theta}\right] - R_t \qquad (4)$$

where θ is the shape of the biological function; R_t is the number of removals, which successively take the value of TR_t and PBR_t.

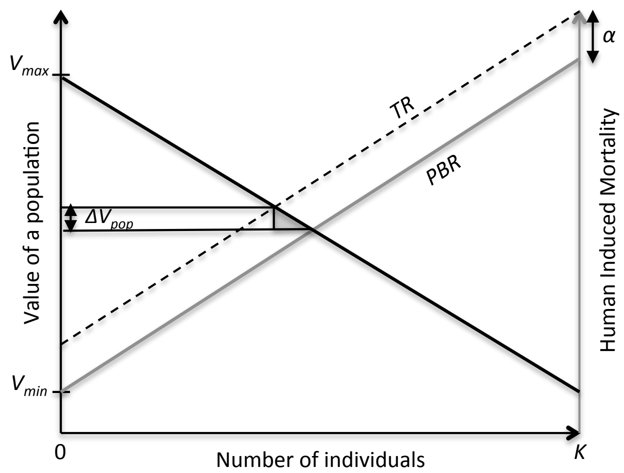

Figure 26. Conceptual illustration of the difference in value between a population where the PBR_t is respected and a population where the PBR_t is not respected (TR_t). To ease the illustration reading, the PBR is represented as a linear function of the number of individuals in the population. In reality, the PBR follows an exponential curve. Conception: Sèbe.

2.3. CASE STUDY: MEDITERRANEAN FIN WHALES

2.3.1.BENEFIT TRANSFER FUNCTION

No study has defined the WTP to protect the Mediterranean fin whale sub-population – to the authors' knowledge. To overcome this lack, we build a benefit transfer function based on the databases of Amuakwa-Mensah (2018) and of the USGS Benefit Transfer Toolkit. These databases contain an extensive number of studies on the definition of the WTP for various animals. After a literature review, the attributes, and their corresponding levels, were selected (Annex 7). A regression was applied to these attributes in the databases to build the benefit transfer function, expressed as follows:

$$\ln v\ (2017\$) = \beta_0 \pm \beta_1 Trend \pm \beta_2 StudyFormat \pm \beta_3 SurveyMode \pm \beta_4 PaymentVehicle \pm \beta_5 PaymentFrequency \pm \beta_6 RespondentUnit \pm \beta_7 \ln IncomeProxy \pm \beta_8 EndangermentStatus \pm \beta_9 SpeciesClassification \pm \beta_{10} \ln Length \pm \beta_{11} \ln Weight \quad (5)$$

where $\ln v\ (2017\$)$ is the natural log of the 2017 base year value of WTP. Trend is the protection objective expected, which is characterized by tow levels: increase and no diminution. The *"increase level"* conveys a willingness to restore a population, whereas the *"no diminution"* level conveys a willingness to have at least no more depletion of the said population – aka conservation (*stricto sensus*). StudyFormat is the way the study is administered – by mail, face to face, internet, mixed, or phone. SurveyMode describes the type of method used for the valuation study – contingent valuation (CV), choice experiment (CE), or hybrid. PaymentVehicle is the way the payment of the WTP is proposed in the original study. PaymentFrequency is the frequency of payment of the WTP proposed in the original study. RespondentUnit describes the scale at which the WTP is expressed – per person or household. The IncomeProxy is represented by the gross domestic product based on purchasing power parity (GDP-PPP) of the country on which the survey takes place – data from World Bank Group. EndangermentStatus is defined by two levels: endangered or not endangered. The endangered status corresponds to the Vulnerable (VU), Endangered (EN), critically endangered (CR) status of the IUCN, and of the endangered and threatened status of the U.S. Marine Mammal Protection Act. SpeciesClassification is composed of eight levels describing the belonging of the studied species to the animal reign (e.g., bird, marine mammal). Finally, the size of the species studied is defined by the Length and Weight. The coefficients of the benefit transfer function are expressed in Table 13.

Table 13. Benefit transfer function coefficients.

Variable	Model coef	Model se
Constant	0.518	1.805
PROTECTION OBJECTIVE (ref=Increase)		
NoDiminution	-0.274#	0.162
STUDY PARAMETERS		
STUDY FORMAT (ref=Mail)		
FaceToFace	1.276***	0.306
Internet	0.229	0.289
Mixed	-0.777#	0.399
Phone	0.787#	0.398
SURVEY MODE (ref=CV)		
CE	-0.635*	0.244
Hybrid	-0.221	0.455
PAYEMENT VEHICLE (ref=Tax)		
TrustFund	-1.292***	0.189
Bill	-0.649#	0.349
Unspecified	-0.929*	0.376
Membership	-1.243***	0.309
PAYMENT FREQUENCY (ref=Annually)		
Monthly	-2.593***	0.323
Once	-1.2***	0.21
Unspecified	-2.593*	0.323
RESPONDENT UNIT (ref=perHousehold)		
PerPerson	-0.554*	0.278
SITE PARAMETERS		
INCOME PROXY		
ln(GDP PPP)	0.475**	0.151
SPECIES CHARACTERISTICS PARAMETERS		
ENDANGERMENT STATUS (ref=Endangered)		
NotEndangered	-0.223	0.189
SPECIES CLASSIFICATION (Ref=MarineMammal)		
Bird	-0.185	0.344
MarineFish	-0.71*	0.323
FreshwaterFish	-1.178**	0.446
FreshwaterMammal	-0.558	0.755
DiadromousFish	-0.349	0.306
MarineReptile	-0.079	0.308
TerrestrialMammal	0.039	0.252
SIZE		
Ln(Length)	0.326	0.233
Ln(Weight)	-0.11	0.083
Observation	112	
R-squared	0.859	
Adj. R-squared	0.816	

*** p<0.001, ** p<0.01, * p<0.05, # p< 0.1

2.3.2. APPLY BENEFIT TRANSFER TO THE CASE OF MEDITERRANEAN FIN WHALES

The Mediterranean fin whale sub-population is composed of ca. 2,500 individuals (Laran et al., 2017). The shipping-related threats to this population are exacerbated by one of the world's highest ship density, with 13% of the world sea trade conservation in the Mediterranean (Equasis, 2017; IWC-ACCOBAMS, 2012; Panigada et al., 2006). Entanglement and other human-induced indirect impacts (e.g., pollution, climate change) also threaten this sub-population (Panigada and di Sciara, 2012). Further, the resilience of this sub-population to disturbances is assumed to be low, as the semi-enclosed basin characteristic limits exchanges with populations outside of the Mediterranean (Notarbartolo di Sciara et al., 2016). For these reasons, the fin whale population is considered as Vulnerable, according to the IUCN Red List, and voices arise to revise down this status to a more critical categorization (Notarbartolo di Sciara, 2016; Panigada and di Sciara, 2012). Parameters used for the definition of the value of protecting the sub-population and of the cost of averting a whale fatality are expressed in Table 14.

Table 14. Mediterranean fin whale's parameters used in this study.

Life cycle parameter (at *t*)	Code	Value	Source/Comments
Abundance	N_t	2,500	The abundance value from Laran et al. (2017)
Carrying-Capacity	K	12,178	The carrying-capacity is defined as 70% of the pre-whaling abundance (Wade, 1998). The worldwide current fin whale abundance is considered to be 14.37% of the pre-whaling abundance (Pershing et al., 2010). Hence, the carrying-capacity calculated is an estimation to illustrate our reflection.
Intrinsic rate of increase	r	0.04	The intrinsic rate of increase was selected from Taylor *et al.*, (2007) and represent a pre-disturbance value.
Recovery factor	F_r	Variable	The recovery factor is here expressed as F_r =0.1+0.4N_t/K, so it cannot exceed 0.5 for a conservative effect on the model (Gerber et al., 2014)
Shape of the biological function	θ	1	The shape of biological function is fixed at 1 to follow the linear hypothesis (Gilpin et al., 1976)
Total removals	TR_t	Variable	The total removals – not including natural mortalities – in the population is a variable of the model
Average Length (m)	L	22	(Shirihai and Jarrett, 2007)
Average Weight (kg)	W	43,900	(Shirihai and Jarrett, 2007)

For our case study, we used the reduced form of the benefit transfer function (Equation 7) and estimated the WTP per person, per year, through a tax fee for the conservation of the fin whale population. To assess the willingness to pay minimum v_{min} and maximum v_{max} for the Mediterranean fin whale sub-population conservation, we replace the EndangermentStatus attribute by the appropriate level to convey the difference between the two values.

$$\ln \text{WTP}(2017\$) = 0.518 - 0.274\text{Trend} - 0.554\text{PerPerson} + 0.475 \ln \text{GDP PPP}$$

$$-0.223\text{EndangermentStatus} + \ln 22 + \ln 43900. \qquad (6)$$

To assess the minimum V_{min} and maximum V_{max} value of protecting the Mediterranean fin whale population, we applied the Equation 1 to the estimated value of v_{min} and v_{max} (Equation 6). We then calculated the cost of averting a whale fatality using Equation 3[38].

2.4. RESULTS: VALUE OF IMPLEMENTING RULES TO AVERT A MEDITERRANEAN FIN WHALE FATALITY

Based on the benefit transfer function, we estimated the minimal v_{min} and maximal v_{max} willingness to pay per person to protect the Mediterranean fin whale sub-population. These values vary depending on the location of the inhabitants, because the benefit transfer function takes into account the GDP-PPP of each country, and the WTP distance-decay relationship (Fig. 27). We use the Equation 1 to define the minimum V_{min} and maximum V_{max} value of protecting the Mediterranean fin whale population, and Equation 2 to define the value V_t when $\mathrm{N_t} = 2{,}500$ individuals:

$$V_{min} = \ \$20{,}128{,}050{,}428 \text{ (US\$2017)}$$

$$V_{max} = \ \$26{,}977{,}790{,}662 \text{ (US\$2017)}$$

$$V_{2017} = \ \$25{,}532{,}058{,}838 \text{ (US\$2017)}$$

Using Equation 3 and 4, we defined the cost of averting a Mediterranean fin whale fatality:

$$\varphi_{2017} = \$562{,}462 \text{ (US\$2017)}$$

[38] Our study is theoretical. We then do not know the value of TR_t. We assume that $TR_t = PBR_t + 1$ (one death over the PBR)

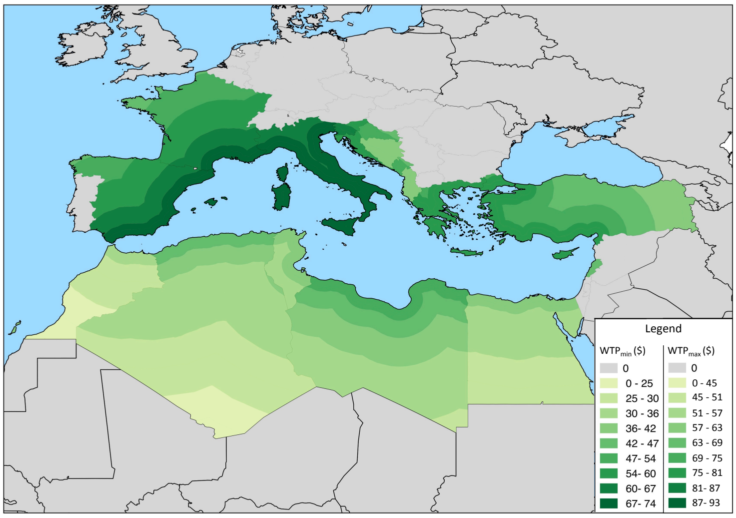

Figure 27. Variation in the willingness to pay v_{min} and v_{max} depending on the location. Conception: Sèbe.

3. POTENTIAL USES WITHIN MARITIME RISK ASSESSMENT: RISK EVALUATION CRITERION

Within maritime risk assessments, risk evaluation criteria are used to evaluate the acceptability of risk (IMO, 2018a). Originally, these criteria were referred as risk acceptance criteria, but the wording risk evaluation criteria were chosen in the IMO context (Skjong, 2002). These criteria were implemented to include environmental losses as economic consequences of the maritime activities; as the consequences of the shipping industry's benefits may not be acceptable for society (Skjong, 2002). Several ways exist to use these risk evaluation criteria (Skjong et al., 2005), but the next section highlights one ways to use it within the FSA (Psaraftis, 2008), in the context of proposing solutions to mitigate collision between ships and Mediterranean fin whales.

3.1. APPLICATION OF THE RISK EVALUATION CRITERION TO THE FSA

As mentioned previously, 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"* (IMO, 2018a). At the FSA fourth step, the guidelines propose to assess the cost-effectiveness ratio of proposed solutions, in order to define their efficiency and to guide decision-makers' recommendations (Step 5). To help decision-makers decide between several solutions, their ratios are compared to the *"maximum incremental cost-effectiveness ratio acceptable"* [39] for human safety (Culyer, 2010), aka the Cost of Averting a Fatality (CAF; Equation 7; IMO, 2018). For oil spills, the Cost to Avert one Tonne of Spilled oil (CATS) has been defined as this maximum incremental cost-effectiveness ratio acceptable (Kontovas et al., 2010). According to the guidelines, a specific risk reduction solution should be recommended for adoption if the value of its cost-effectiveness ratio is below this specified acceptable ratio; otherwise, this solution should not be recommended.

$$\frac{\Delta C - \Delta B}{\Delta R} < \lambda \qquad (7)$$

where, ΔC is the cost per ship of the solution under consideration; ΔB is the economic benefit per ship resulting from the implementation of the solution; ΔR is the risk reduction depending on the number of fatalities averted, induced by the solution; λ the maximum incremental cost-effectiveness ratio acceptable.

3.2. EVALUATION OF MEASURES TO REDUCE THE COLLISION RISK TO FIN WHALES IN THE MEDITERRANEAN

For whales, Sèbe et al., (2019) advocated for the definition of the Cost of Averting a Whale Fatality (CAWF). This exploratory chapter proposed a way to calculate the cost of averting a whale fatality, which can be used as a *"whale"* risk evaluation criterion in cost-benefit analysis, or, in our case, in the FSA Cost-effectiveness analyses. This criterion represents the *"whale"* maximum incremental cost-effectiveness ratio acceptable ($\lambda = \varphi_{2017} = \$562{,}462$ for Mediterranean fin whales). We can now compare this criterion to solutions' cost-effectiveness ratios in order to simulate the IMO decision for these solutions.

In the Mediterranean, the only solution economically assessed is the Real-Time Plotting of Cetaceans System (REPCET). This system creates a network between ships for them to communicate about whales' sightings in order to avoid collisions (Couvat et al., 2016). REPCET costs $120,000 over the 25 years of a ship's lifetime (Couvat, 2015)[40]. To be noted that these

[39] Referred as the cost-effectiveness criterion in Chapter 1.
[40] According to the FSA guidelines, the cost-effectiveness ratio must be calculated over the lifetime of a ship. 25 years represents a realistic ballpark number (Stopford, 2009).

costs are underestimated as they do not take into account operational costs, such as additional fuel costs, or costs due to delays in ports of call (Kite-Powell and Hoagland, 2002). Regarding whale mortality, Chapter 4 of this thesis estimated the human-induced direct mortality – collision and entanglement – of fin whales in the Mediterranean at between 25 and 67 ind/y (PBR=5). By assuming that the collisions are responsible for half of the mortality, the number of collision-related mortality beyond the PBR is between 10 and 31 ind/y. As the REPCET is not a perfect system, we here assume that it can avoid 20% of whales' fatalities per year; therefore, between 2 and 6 ind/y (50-155 ind/25y). The cost-effectiveness ratio of the REPCET solutions is then theoretically between $774 and $2,400 per whale saved. To be noted that these approximations are not accurate, as the operational costs are not accounted, and that uncertainties remain around the number of dead whales. Yet, even if the costs were 100x superior to the current estimated costs, the cost-effectiveness ratio would be inferior to the risk evaluation criterion defined in our study ($562,462). Consequently, the IMO would recommend the REPCET solution – if the criterion were to be accepted within the FSA guidelines (IMO, 2018a).

Beyond the scope of the IMO and the FSA, the comparison between the risk evaluation criterion and the partial costs of REPCET exposes a possible low economic impact of mitigation solutions for the shipping companies. However, as mentioned before, the literature shows that the compliance to these solutions is often low (e.g., Chion et al., 2018; Freedman et al., 2017). Two factors can be highlighted as reasons for this noncompliance with inexpensive solutions. First, even if the solutions are inexpensive, their implementation might be challenging due to logistical factors (e.g., port call loss; Stopford, 2009; see Chapter 3). Second, the potential loss of competitiveness can be highlighted as a contributing factor (Gritsenko and Yliskylä-Peuralaht, 2013). For example, an open letter to the IMO from more than 120 shipping companies recently advocated for mandatory measures regarding gas emission to achieve the Initial Greenhouse Gas Strategy for international shipping (Anonymous, 2019). This letter showed the willingness of the companies to reduce their emission to respond to global change, but also showed that without international mandatory measures, the shipping companies could not act on themselves, as they would lose competitiveness with other non-involved companies (Gritsenko and Yliskylä-Peuralaht, 2013; Psaraftis, 2019). The same principles could govern whale-ship collision solutions implementation. Consequently, the IMO recommendations – for example, through the FSA and the risk evaluation criterion – could be crucial for whale conservation.

4. LIMITATIONS

4.1. EXISTENCE VALUE LIMITATIONS

4.1.1 EXISTENCE VALUE, CURRENTLY THE BEST VALUATION OPTION?

Our approach uses the existence value to put a monetary value on whales. As mentioned before, the monetization of life value is often criticised. To prevent this monetization, Babcock (2013) advocated for a change in the whale preservation norm. Despite its appealing aspects, this solution undergoes two issues. First, the implementation of a whale preservation norm would take a tremendous amount of time, which is inconsistent with the urgency that requires the state of many whale populations (Caswell et al., 1999; Rendell and Frantzis, 2016). Second, the implementation of such norms can fail. As an example, the norm adoption stipulating that commercial whaling was no longer acceptable partly failed (1986 International Whaling Commission Moratorium; Bailey, 2008; Kojima, 2019). The combination of these two issues shows that a whale preservation norm from shipping can take a long time to reach the public, especially given the invisibility of the collision issue (Peel et al., 2018), and may be a failed attempt.

Other approaches emerged to prevent the use of monetary values for living beings. The ecosystem services (ES) or the nature contribution to people (NCP) approaches have been advocated to overcome the monetization philosophical – and technical – limitations. These approaches rely on the – monetary or not – evaluation of the contributions of nature to people. The ES and NCP approaches give an insight into the overall value of the ecosystems – total economic value –, whereas the existence value only conveys a part of the living being’s value (Beaumont et al., 2008).

However, when studying charismatic endangered megafauna – such as whale’s populations -, the ES or NCP also exhibit limitations. While preventing on putting a monetary value on most of the contributions, these approaches are not able to quantitatively assess all contributions (Cook et al., 2020; Nijkamp et al., 2008; Riisager-Simonsen et al., 2020), and the addition of the monetized values is often not possible due to a potential redundancy in the accounting (Böhnke-Henrichs et al., 2013).

Further, the place of biodiversity – and more precisely of charismatic endangered megafauna – in these approaches can be debated. Within the ecosystem service approach, the biodiversity was highlighted as a kind of insurance against changes of state in ecosystems (Admiraal et al., 2013; Baumgärtner, 2007; Yachi and Loreau, 1999). In other words, the loss of a species can be compensated by another one, which supports similar services. Hence, biodiversity is essential for ecosystem resilience and its services (Admiraal et al., 2013; Chillo et al., 2011; Sundstrom et al., 2012). While the biodiversity begins to be integrated into the ecosystem services, the individual species aspect seems to be overlooked, especially for endangered charismatic species (e.g., panda, tiger, whale). The number of these species' individuals is often low, and despite their high unitary contribution to the ecosystem, their total contribution, as a population, is usually low. In other words, while a whale provides a more significant contribution to the productivity of an ecosystem than a fish (Roman et al., 2014), the total contribution of the whale population to the productivity of the ecosystem – at the population home range scale – is lower than the one by the fish population. Consequently, the removal of one whale might not lead to a significant change in the contribution values, but might be significant for the population's survival (Admiraal et al., 2013; Freeman et al., 2014). Therefore, there is a dichotomy between the unitary importance of one whale in the ecosystem, and its intrinsic importance for the population.

To sum up, the monetization through the existence value, the implementation of norms, or the valuation through ecosystem services each has its limitations. However, one known fact is that the existence value is high for charismatic species, such as whales. For this reason, and while other avenues of research can be investigated for the definition of the *"whale"* risk evaluation criteria, we chose to investigate the existence value for this preliminary study.

Megafauna existence value, such as whales, highly dominates other species' contributions (Jacobsen et al., 2012). For example, in Sweden, Nunes, van den Bergh and Nijkamp (2001) demonstrated, through a contingent valuation, that 70% of the WTP to protect 300 endangered species was attributed to the wolf – a charismatic species. Other studies showed the dominance of these species' existence value over other species' values (Carlsson et al., 2003; Eggert and Olsson, 2009; Molina et al., 2019). Also, the importance of evaluating the existence value for the recovery of salmons – a charismatic endangered species – has recently been highlighted (Mckean and Johnson, 2019).

The dominance of these species' existence value led to the use of this value as a social demand within ecological-economic frameworks. Formally theorized by Eiswerth and van Kooten (2009), this approach has notably been used in agriculture for some time (Drechsler and Settele, 2006; Gerling et al., 2019; Johst et al., 2002). Gerber et al. (2014) applied this approach to whale conservation, but created a market between conservationists and whalers, which triggered a lot of criticisms (Smith et al., 2014). However, despite ethical objections triggered by Gerber et al. (2014), their approach opens-up the discussion to the use of ecological-economic frameworks (Gerber et al., 2014b) for whales. Beyond philosophical concerns, research needs to investigate these kinds of ecological-economic approaches using existence value for whales as this value might be one of the highest of the animal realm (Amuakwa-Mensah, 2018; Christie et al., 2006). This value can be used, as our preliminary research shows, as decision-making criterion – for example, within the FSA framework.

4.1.2. EXISTENCE VALUE TECHNICAL LIMITATIONS

Besides ethical issues and the lack of viable alternatives to the use of existence value, our approach faces other technical limitations related to the valuation method.

The *"free-ranging"* bias represents one of the existence value calculation's limitations. This bias depicts the distinction between social and private demand. In other words, there is a difference between what people state they are willing to pay, and what they would really pay if they have to. This bias may be seen as void for the risk evaluation criterion definition, as the price is not seen as potential internal funding for conservation (Garrod et al., 2012; Stithou and Scarpa, 2012), but as a representation of the people willingness to have viable whale populations. The compensation is then hypothetical (Kontovas, 2011). Nonetheless, the refinement of the WTP estimations is needed, in particular, to avoid bias due to lexicographic preferences (Veisten et al., 2006).

Our study assessed the value of protecting the Mediterranean fin whale population, disregarding the sperm whales (*Physeter macrocephalus*), another at-risk population in the Mediterranean (Frantzis et al., 2015; Rendell and Frantzis, 2016). However, as Beaumont et al., (2008) said that "*the willingness to pay to maintain one sea mammal species is equivalent to the willingness to pay to maintain all sea mammal species"*. Consequently, the WTP value estimated must theoretically be the same for sperm whales – in reality, slightly different using the benefits transfer function. If the two populations were to be considered as one unit (e.g., the Mediterranean whale stock), the value of protecting the stock would increase, as sperm whales' individuals would be added to the 2,500 fin whales individuals. The addition of the two populations would create an issue with the conservation target model, as the PBR will differ for the two populations, and a simple addition of the PBR might be too simplistic. Also, the PBR concern all the human-induced direct mortality, hence entanglements and collisions. Consequently, the number of removals described by the PBR is not only attributable to collisions, and further researches are required to investigate this limitation.

4.2. RISK EVALUATION CRITERION LIMITATIONS

Similar to Bulte and Van Kooten (1999), when calculating the cost of averting a whale fatality that is used as a risk evaluation criterion, we assume a linear relationship between the endangerment status and the WTP. However, as it has been shown in the literature that this linearity is an oversimplification (Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008), mainly due to the diminishing marginal returns or the increasing marginal value of scarcity (Richardson and Loomis, 2008; U.S. EPA, 2014). As a result of this oversimplification, the risk evaluation criterion defined in our study is constant. Though, the more the population is in danger, the more the value of a whale should be high (Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008). In the cost-effectiveness analyses, the constant criteria, such as the ones for oil spills or gas emissions, have recently been criticized (Eide et al., 2009; Skjong et al., 2005), as they only work for small risk reductions (Kontovas, 2011). Further studies are required to define a non-linear cost of averting a whale fatality, similarly to what has been done for oil spill (Kontovas and Psaraftis, 2008).

Further, the use of the *"whale"* risk evaluation criterion within the FSA may introduce a double counting into Equation 7. Indeed, the benefits in this inequation lies within the risk reduction induced ΔR and the value of one whale $\boldsymbol{\lambda}$. The underlying theory of the cost-benefit and the cost-effectiveness analysis demonstrate some double counting with the use of these values (Annex 7; Kontovas, 2011). Also, investigations are needed to integrate the *"whale"* risk evaluation criterion – defined in this study or not – into cost-benefit assessment, and to combine the environmental risk and the fatality risk, as it has been discussed for oil spills (Psaraftis, 2008). Further research is therefore needed to overcome these limitations.

5. CONCLUSIONS AND FUTURE RESEARCH

In our study, we used the existence value to estimate the cost of averting a Mediterranean fin whale fatality as a risk evaluation criterion. This work is exploratory and uses basic theories, which have been improved in recent years. However, as it is a first attempt to design such a criterion, this work has the merit to set some basis, which might be improved in the coming years with the processing of the identified limitations (see the previous section).

The adoption by the IMO of a *"whale"* risk evaluation criterion might help decision-makers evaluate solutions to reduce collisions – or other whale-ship related interactions. As these solutions generally bear more costs than benefits for the shipping industry, this criterion might highlight the shipping industry acceptable level of investments for whale protection (Skjong et al., 2005). Furthermore, the use of a risk evaluation criterion by conservationists – the ones that propose solutions – give insights on solutions that are economically not viable for the shipping industry; therefore, helping them to choose solutions that will trigger a high level of compliance from the shipping companies. This criterion might lead to a win-win situation between the shipping industry and conservationist stakes (Makina and Luthuli, 2014). Consequently, the setting of an adequate risk evaluation criterion might increase the number of pro-whale measures approved at the IMO level, as it would increase the transparency of the proposals. With time, the IMO recommended solutions would increase the compliance from the shipping companies with the mitigation solutions, and, therefore, improve whale conservation.

However, further research is required before considering the use of a *"whale"* risk evaluation criterion. Regarding our approach, further investigations are required to overcome the limitations identified, especially the fact that the cost of averting a whale fatality is constant. On one hand, similar approaches to what has been done to overcome this limitation for oil spills can be explored. However, the works on oil spills were based on clean up costs (Kontovas et al., 2011), and there might be a lack of data on whales to perform a similar approach (Chapter 2; IMO, 2018). On the other hand, despite criticisms expressed in this Chapter, the research on the application of ES approaches to whales is only just starting as testifies the recent publication of Cook et al. (2020) on the categorization of whale ecosystem services, or the global approach proposed by the International Monetary Fund (Chami et al., 2019). Future research may provide insights on ways to solve the dichotomy between the unitary importance of one whale in the ecosystem, and its intrinsic importance for the population. In the end, the ES may be integrated into the IMO decision process to deal with environmental aspects (Andersson et al., 2017).

GENERAL DISCUSSION

"There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion."

D.H. Meadows, 2008

The general discussion is composed of three sections. The first section summarizes the key findings of the thesis. The second section discusses the implication of these findings for whale conservation and policy-making. Finally, the third section highlights the limitations of the work, but also the research perspectives that this work opens up.

1.THE KEY FINDINGS OF THE THESIS

In Chapter 1, we conceptualized the use of the International Maritime Organization (IMO) risk assessment, namely the Formal Safety Assessment (FSA), to integrate the human and ecological dimensions of the whale-ship collision issue into a standardized process. Until now, the FSA has only be applied to human safety issues (e.g., injury, fatality), and more recently, for oil spill issues (Haapasaari et al., 2015; Kontovas and Psaraftis, 2008). To adapt this framework to whale-ship collision, we have investigated the various FSA steps: (1) identification of hazards; (2) risk assessment; (3) risk control options; (4) cost-benefit assessment; and (5) recommendations for decision-making. We found that the implementation of the FSA for the whale-ship collision management could be decisive for whale conservation. The compliance with mitigation solutions is often low (e.g., McKenna et al., 2012), as the current solution proposals rarely take into account their economic and logistic impact on the shipping industry (e.g., IMO, 2012). The use of the FSA framework would enable decision-makers to have a complete overview of the issue. This transparency brought by the integration of both the human and ecological dimensions would facilitate the decision-makers recommendations, the government enforcement, and/or the industry's willingness to act (Ayyub et al., 2007; Kirchler et al., 2008; G. K. Silber et al., 2012; Silber et al., 2015; Whitney et al., 2016). However, two main impediments to using the FSA adaptation for whale-ship collision management were identified: (1) the difference in the acceptable risk definition between the shipping industry and conservationists[41]; and (2) the absence of a *"whale"* risk evaluation criterion definition for decision-making.

To improve our knowledge on the economic aspects of the whale-ship collisions, Chapter 2, explored the potential damage to ships after a whale-ship collision. Damage has always been deemed low (Van Waerebeek and Leaper, 2008), but has never been quantified. After collecting data in the various databases and scientific publications, we used the Vanderlaan and Taggart (2007) approach to assess the probability of damage to ships following a collision with a whale

[41] A person who advocates conservation especially of natural resources (Merriam-Webster Dictionary). In this thesis, this word can refer to conservation scientists, MPA managers, Non-Governmental Organization, or other structure/person that acts for the conservation of natural resources.

given both ship length and speed. Despite variations that depend on the type of ship, our model estimates that overall one in ten collisions with whales leads to ship damage. Passenger ships are in the highest risk category, given their relatively small size and high speed. Moreover, most of the, if but few, human fatalities and injuries reported occur in this ship category. Repair costs due to collisions can reach several hundreds of thousands of dollars, and a loss of income, related to ship inactivity during the repair phase could be even higher than the cost of repair. We then compared the management of damage costs for aviation with maritime transport. For more than two decades, avoided costs have been integrated into collision management for aviation (Dolbeer et al., 2015; ICAO, 2009), whereas these aspects have not been taken into account for shipping. This level of transparency in aviation has contributed to improved management, which in turn has led to the implementation of pro-active mitigation measures (Anderson et al., 2015; Devault et al., 2009). We conclude that these costs should be integrated into whale-ship collision solution proposals to mimic collision management found in aviation.

One of the lessons learned in Chapter 2 is that the management of collision with wildlife is usually systemic, except for whale-ship collisions. To overcome this limitation, Chapter 3 tackled the logistical aspects hampering the shipping industry's compliance with whale-ship mitigation solutions. Some solutions may not be adapted to shipping industry's logistic features of the study site and even an economic assessment would not improve the compliance of the said solutions. Using a choice experiment survey, we tested the preferences of captains and watch officers to two of the most effective mitigation solutions in the literature: speed reduction and avoidance. Results showed a preference to avoid instead of reduced speed in a high-density whale area, especially in coastal waters. This preference is less pronounced for long-distance trips where the implementation of one or the other solution appears to have a lower impact on preference. The shipping industry also prefers to have the choice between the two solutions, instead of having one or the other imposed. The crew prefers to have upstream information on the location of the high-density whale area, up to a certain time (15h11), where there is no added value of having more time to prepare the journey. These results regarding the time of reception of the information confirm insights from Reimer et al. (2016) on the subject and quantify it. Overall, our findings can be used as guidelines for whale-ship collision mitigation solution implementation. The proposed solutions should take into account the type of navigation (e.g., coastal navigation, long-haul travel). For coastal navigation, for instance, conservationists (e.g., researchers, NGOs) should thus propose avoidance rather than speed limitation to ensure shipping industry compliance. The implementation of either solution in the high seas should be considered within IMO schemes such as Particularly Sensitive Sea Areas (PSSA) or Emission

Control Areas (ECA), as the compliance would probably be high given the distances involved in these areas. These long distances allow offsetting the time lost (Brouer et al., 2013). The improvement of dynamic habitat modeling is encouraged to provide better upstream information for crew decision-making (Hampton et al., 2013; Madon et al., 2017; Pimm et al., 2015).

In a systemic approach to whale-ship collision management, it is crucial to take into account simultaneously economic and ecological aspects. To tackle the ecological aspects, Chapter 4 investigates the risk assessment of human-induced direct mortality (HIDM; collision and entanglement; Heyning and Dahlheim, 1990; Kraus, 2005; Williams et al., 2011) in the Mediterranean fin and sperm whale subpopulations – our case study. Taking advantage of the semi-enclosed characteristic of the Mediterranean basin, I used the carcass recovery rate to define the level of severity of HIDM. Unlike other studies, the focus was not on the precise value of the number of HIDM, which is highly variable due to biological and technical factors, but on the consequences of HIDMs on the sub-populations through comparison with management rules (e.g., Limit Reference Points; Curtis et al., 2015). More specifically, while the number of HIDM is usually defined at the scale of an identified hot spot of collision[42], the global impact of HIDMs at the population level is rarely assessed (Brown et al., 2019). This is, however, crucial for decision-makers – at the IMO scale or not – to know the level of threat induced by an activity on the studied whale population or sub-population (notion of acceptable risk; Carwardine et al., 2008; Vanem, 2012). Our approach opened insights into the Mediterranean fin and sperm whale status and conservation perspectives. For fin whales, the incidence of HIDM on the sub-population survival is critical. Depending on some parameters, the HIDMs alone are probably the main cause of depletion of this sub-population. I conclude that the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) should revise its guidelines for individual removals[43] (ACCOBAMS, 2016). Besides which, I am in total agreement with the voices in favor of revising down the Mediterranean fin whale IUCN status from Vulnerable to a more critical IUCN category (Notarbartolo di Sciara, 2016; Panigada and di Sciara, 2012). Regarding sperm whales, mortality causes are more heterogeneous. While entanglement represents the greatest threat amongst HIDM, our results suggest that a tremendous effort should be made to study further and limit indirect impact (e.g., persistent organic pollutants, prey depletion, plastic ingestion), which are most likely the main threats to the survival of this sub-population (Mazzariol et al., 2011; Notarbartolo-Di-Sciara, 2014; Pinzone et

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[42] Studies on entanglement are scarcer as the issue is less visible.

[43] Mortality limit due to HIDM

al., 2015). The improvement of the stranding network effectiveness for identifying the causes of mortality would help refine our results, and assess precisely the contribution of collisions to HIDM (Box. 2 in Chapter 4; Worthy, 1999).

Trade-off between ecological and economic aspects was investigated in Chapter 5, the FSA with a first definition of the risk evaluation criterion for whales. The FSA cost-benefit assessment proposes to assess the solution cost-effectiveness ratios – and not cost-benefit ratios (Annex 7). These cost-effectiveness ratios only account for private costs and benefits to the shipping industry (Huysegoms et al., 2018; Zheng, 2006). Consequently, the costs often outweigh the benefits when a solution proposal is made. To guide decision-makers when this phenomenon occurs, the IMO introduced some risk evaluation criteria (IMO, 2018a). Risk evaluation criteria are useful tools for decision-making as they *"define how risks are measured (metric), the level of risks that are acceptable and the level of investment in risk reduction that are deemed necessary"* (Skjong et al., 2005). Within the FSA, if the cost-effectiveness ratio is inferior to a risk evaluation criterion, the IMO decision-makers should recommend the proposed solution. This criterion has been defined and validated by the IMO for human safety and oil spill, but not for whales (Eide et al., 2009; IMO, 2004b; Vanem, 2012; Vanem et al., 2008). Our approach used an ecological-economic framework based on the value of a whale population to define this criterion for the Mediterranean fin whale population – our case study. Our results show a criterion of $562,462 (US$2017). If the IMO were to adopt the risk evaluation criterion proposed here and given the implementation costs of the Real-Time Plotting of Cetaceans System (REPCET) in the Mediterranean, this solution should be recommended by the IMO. The risk evaluation criterion used in Chapter 5 for the FSA cost-effectiveness analysis, could be implemented in other contexts (e.g., cost-benefit assessments).

2. IMPLICATION FOR WHALE CONSERVATION AND POLICY-MAKERS

2.1. THE IMPORTANCE OF THE IMO FOR WHALE-SHIP COLLISION MANAGEMENT

While whale-ship collision mitigation solutions have been implemented for two decades, a recent push towards international regulatory management of collisions has been published in the literature (Geijer and Jones, 2015; Sèbe et al., 2019; G. K. Silber et al., 2012). This thesis shows that, at the local and regional level, the compliance with, and the applied effectiveness of mitigation solutions is often low, with few exceptions (e.g., Constantine et al., 2015; Sèbe et al., 2019). Compliance increases through the implementation of mandatory solutions – or incentives (Lagueux et al., 2011; McKenna et al., 2012). For shipping, the IMO is the main organization able to set such mandatory rules for whale-ship collision management at the international level (Geijer and Jones, 2015). Our study demonstrated that for aviation, wildlife conservationists have, for a long time, used the IMO counterpart, namely the International Civil Aviation Organization (ICAO), to manage wildlife-aircraft collisions (Allan et al., 2002; Devault et al., 2009; Dolbeer and Wright, 2009; ICAO, 2017b, 2017a, 2012). This integration of wildlife management in international aerial transportation functioning led to the implementation of pro-active solutions (Anderson et al., 2015; Devault et al., 2009), which has not been the case in whale-ship collisions management (Chion et al., 2018a). Of course, these standardized processes were not implemented solely for the protection of wildlife (Annex 3). The primary reason for adopting these processes was more for human safety and aviation security rather than wildlife protection. (Popp and Boyle, 2017); however, the integration of human and aviation safety had a direct beneficial effect on wildlife safety, giving rise to a win-win situation for both conservation and industry alike. (Makina and Luthuli, 2014).

By emulating the ICAO example, the IMO may well be able to solve some of the challenges faced in the management of whale-ship collisions. The challenges are twofold. First, place-based management – Marine Protected Areas (MPA) – constitutes the primary protection tool for whales (Notarbartolodi Sciara et al., 2016). However, the MPAs protection effectiveness is often not enough as whale home ranges often exceed MPAs boundaries (Geijer and Jones, 2015). For example, in the Mediterranean, it has been shown that the fin whale main habitat crosses the Pelagos sanctuary boundaries (Geijer et al., 2016), which explains the recent push to extend its frontiers (IWC, 2019). Second, any solution proposed at the national level has a limited effectiveness (see Introduction; section 1.2.2.; Stopford, 2009). For example, the French national Law for the Biodiversity recently imposed that flag state ships larger than 24m crossing the Agoa and Pelagos sanctuaries install an inter-ship whale observatory network (e.g., REPCET; République Française, 2016). Hence, French ships navigating within these two sanctuaries are compelled to install a mitigation solution, but foreign ships crossing these same sanctuaries are not. This distinction imposes a disadvantage on the French companies, who are obliged to have added economic and logistic constraints when using the REPCET device. If this requirement were to be applied by the IMO – as long as the Member states agree –, it would lead to the enforcement for all ships, independent of their flag. This would then remove unfair competitiveness between shipping companies (Gritsenko and Yliskylä-Peuralaht, 2013).

To sum up, this thesis highlights the need for international regulatory management for whale-ship related issue managements. The international agreements, such as the International Whaling Commission (IWC) or ACCOBAMS, work towards increased whale protection, but often have limited means, and primarily focus on international cooperation. As previously mentioned, the IMO is a United Nations organization that deals with all aspects of maritime safety and the protection of the marine environment (Chapter 1). The success of some proposals emitting from this organization, highlighted its protection potential for whales against the negative impact of shipping (e.g., Freedman et al., 2017; Lagueux et al., 2011). The IMO exhibits key features for whale-ship collision management: (1) being a *"long-standing authority in international shipping"* (Geijer and Jones, 2015); (2) dealing with *"all aspects of maritime safety and the protection of the marine environment"* (Kontovas and Psaraftis, 2009); (3) producing *"conventions which become law when they are enacted by each maritime state"* (Stopford, 2009); (4) offering a *"mechanism to implement mitigation solutions whatever the scale"* (Geijer and Jones, 2015); (5) representing *"more than 170 member states"* (Geijer and Jones, 2015). In other words, the IMO offers a legal framework for managing collisions similar to the ones found in wildlife-vehicle collisions, notably in aviation.

2.2. THE IMPORTANCE OF THE ECONOMIC AND LOGISTIC ASSESSMENTS

Notarbartolo di Sciara (2016) stated: *"Conserving [...] marine mammals [...] too often clashes with economic interests, and when a compromise is sought, economic concerns always get the upper hand; in most cases, however, compromise is not even considered, and conservation remains a hollow term"*. While true, our work shows that this statement glosses over the fact that the economic dimension is often left out of the whale-ship collision solution equation (Chapter 5). Contrastingly, one can notice that economic and environmental considerations are taken into account in the airway, railroad, and terrestrial road collisions management (Jaarsma, 1997; Kociolek et al., 2015).

To fully comprehend the reason for this absence, this thesis looked at the discrepancy and the reasons why the economic impact of whale-ship collision mitigation solutions is overlooked. Put simply, conservationists express the value of a solution in terms of reduced risk to whales. However, when companies ask the simple question of how much this solution will cost, the conservationists usually do not have an answer. In Chapter 1, we defined the types of cost and benefit that could be integrated into the analysis of whale-ship collision mitigation solutions: (1) implementation cost / mitigation solution installation; (2) maintenance cost; (3) operation cost, including direct and indirect such as fuel consumption or costs associated with delay in the time of arrival; and (4) benefit from avoiding costs, such as repair following collisions.

In the literature, few studies have tried to assess the economic impact of mitigation solutions on the shipping industry. Couvat (2015) assessed the cost of installing a technical solution (REPCET) – omitting the assessment of operational cost (e.g., fuel consumption; loss of port call). Direct and indirect operational costs have been assessed by Kite-Powell and Hoagland (2002), or Nathan Associates Inc (2012) for the U.S. East coast, based on different scenarios (e.g., SR, DMA), and more recently, Gonyo et al. (2019) studied these costs for the U.S. Channel Islands region. Also, the cost of maintenance (Ben-Daya et al., 2009) was not apparently assessed to our knowledge. Finally, some attempts to define standard costs for technical solutions have been undertaken in the past, but have not been pursued (Couvat and Gambaiani, 2013; Silber et al., 2008b). Our study in Chapter 2 is the only study – to our knowledge – that proposes first estimates of the avoided costs.

Through the various Chapters of this thesis, I have tried to highlight the stakes behind the integration of the economic and logistic dimensions. Within the IMO regulatory framework, a more systemic approach would give a global overview of the ecological and economic impact of a solution to the decision-makers, and thus, improve the transparency of recommendations (Chapter 1). As mentioned before, the IMO currently, recommends solutions only if they are already implemented by the Member states concerned (IMO, 2016a). According to our research, before any proposal to the IMO can be made, submitting stakeholders should carry out a feasibility study of the shipping industry's logistics within the policy site (Chapter 3). If the solution is logistically viable, a complete assessment of the costs identified in Chapter 1 should be undertaken. Finally, the costs, and potential benefits, should be weighed against the risk reduction induced – given that the level of risk has been defined (Chapter 4) – to assess if the costs of implementing a solution are economically disproportionate, through, for example, a risk evaluation criterion (Sèbe et al., 2020).

Overall, this thesis highlights that the cost of whale-ship collision mitigation solutions appear to be within the range of acceptable shipping industry expenses. Consequently, by proposing a solution supported by an economic assessment of its impact, the shipping industry compliance with the said solution should increase in comparison to the current state, where there is a lack of information that hinders stakeholders' actions. Estimation of whale-ship collision mitigation solution costs by conservationists is, therefore, crucial for whale protection. As it will be beneficial to both the shipping industry and conservationists, the integration of economic dimensions can then improve mutual trust – or at least create a bridge – between these stakeholders (Kirchler et al., 2008; Lent, 2015).

3. LIMITATIONS AND PERSPECTIVES

3.1. LIMITATIONS TO THE IMPLEMENTATION OF SYSTEMIC APPROACHES FOR WHALE-SHIP COLLISION MANAGEMENT

While the systemic approach of whale-ship collision management is promising, its implementation at the IMO level remains challenging. This section highlights the main identified constraints to this implementation: the decision time, and the backlog in marine environmental policy.

3.1.1. DECISION TIME

Conservation and the shipping industry work to different time lines, which hinder the implementation of whale-ship collision solutions. The decision process of United Nations agencies, such as the IMO, can be long, given the number of Member states, and stakes at play (Hosli and Dörfler, 2019; Psaraftis, 2019). Kontovas and Psaraftis (2009) highlighted this point with the example of an FSA that took 2.5 years to be completed. Furthermore, while the IMO may recommend a mitigation solution, its enforcement relies on the solution being enacted into the contracting parties' laws (O'Leary et al., 2020; Stopford, 2009). Whale conservation demands more urgent action. While many populations are recovering since the whaling moratorium, some others are confronted with the competitive exclusion of expanding human activities at seas (Magera et al., 2013; D. J. McCauley et al., 2015). The harvesting and competitive exclusion phases (Introduction) represents a small period in comparison to the time that whales have existed (~30 million years; Deméré et al., 2008), and the whale has not had the time to evolve quickly enough to adapt to these emerging threats (Malhi et al., 2016; Sandom et al., 2014). For example, it has taken a longtime for whales to react to the sound of approaching ships (Nowacek et al., 2004). Recently, Szesciorka et al. (2019) showed that whales in spite of being exposed to ship sounds for a long time are only now starting to be alerted by approaching ships. In addition, populations at risk of extinction due to HIDM were identified only recently (couple of decades; Cates et al., 2016; IWC, 1999a; Ritter and Panigada, 2019). Consequently, all these factors advocate for a swift response from conservationists through the proposal of effective solutions, often without analysis of the impact that these solutions will have on the shipping industry. The time frame of these solutions is rarely beyond the short-term. Therefore, these solution proposals lack a systemic approach providing a global and long-term overview of the issue. In order to limit the dichotomy between conservation and shipping temporal dimension, I advocate for local and regional short-term solutions for endangered whale species, while developing long-term solutions at the IMO level.

3.1.2. BACKLOG IN MARINE ENVIRONMENTAL POLICY

The backlog in policy for the marine environment might be an impediment to the implementation of a holistic approach, such as the FSA. As previously mentioned, the management of wildlife collisions appears better developed in terrestrial and aerial transportation than in shipping. This backlog might be partly due to the difference in the constraints of these industries. Indeed, several constraints are apparent before constructing a terrestrial road or an airport (Tsai and Chang, 2012), but do not apply for maritime roads. First, land is, for the most part, a private good (Kelly and Allan, 2006), whereas the seas are considered as a public good. Consequently, purchasing the land is the first step for road and airport construction. Additionally other constraints come into play, such as national and international environmental impact assessment (EU, 2001, 1985) or physical constraints to road construction (e.g., mountains, clay soil; Rahmat and Kinuthia, 2011; Samani et al., 2010). Train and truck transportation mode have to adapt to these roads, which are not going from point A to point B in a straight line (Fig. 28). In contrast, the shipping transportation mode – and to a lesser extent, for some points, aviation – does not have to *purchase* roads or carry out environmental impact assessments on these roads, with the exception of harbor entrances (EU, 2001, 1985), and has nothing to avoid except for land and some coastal waters (e.g., TSS). Consequently, ship journeys are optimized, as their journey from point A to B is more or less in a straight line (Fig. 28). Thus making maritime transportation the most efficient transportation mode (Stopford, 2009). The lack of physical constraints also partly explains why the shipping industry is characterized by less drastic regulations than other transportation modes; the late implementation of the maritime traffic regulation is the perfect illustration of this (e.g., UNCLOS). As a result, the implementation of a holistic approach is less common for maritime transportation than for other transportation modes (Jaarsma, 1997; Kociolek et al., 2015).

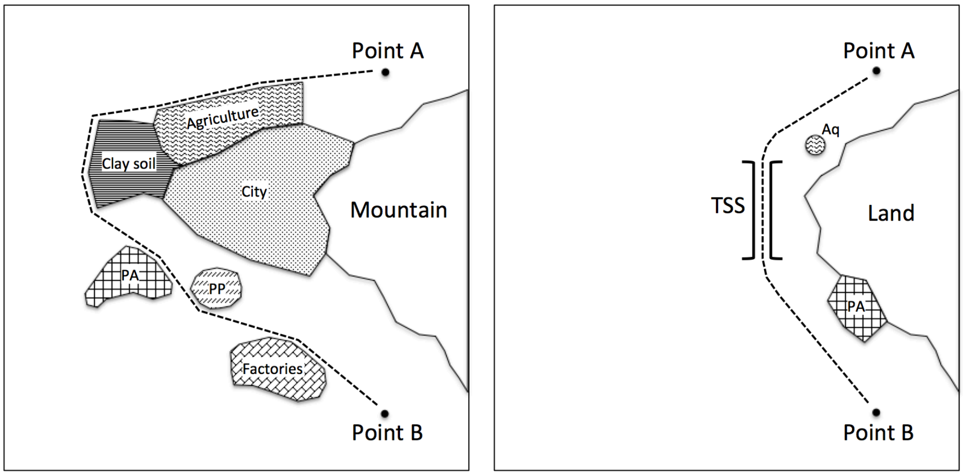

Figure 28. Illustration of the difference of constraints between land (left) and sea (right) transportation. For an identical theoretical journey, ships have fewer constraints (e.g., regulation, physical constraints) than cars or trucks, and are then a more efficient transportation mode. PA, PP, and Aq respectively stand for Protected Area, Private Property, and Aquaculture. Conception: Sèbe.

3.2. PERSPECTIVES

The last sub-section highlighted some temporal and spatial limitations that are challenging to overcome for implementing a systemic approach to whale-ship collision management. This next section will focus on research perspectives that arose from within the systemic process itself.

3.2.1. ACCEPTABLE RISK

The definition of acceptable risk differs between conservationists and the shipping industry. For the – shipping – industry, the acceptable risk corresponds *to "the level of human, property [, or environmental] loss that can be tolerated by an individual, household, group, organization, community, region, state, or nation"* (Svalova, 2018). In the FSA framework, the recommended approach to acceptable risk is the As Low As Reasonably Practicable (ALARP) one. This approach integrates both risk and cost. Indeed, the ALARP is referred to as a level of risk, for which further investment of resources for risk reduction is not justifiable (IMO, 2018a). Three regions are considered in the ALARP approach (Fig. 29). First, the inacceptable region is where the risk exceeds the average acceptable risk by more than one order of magnitude. When the risk is defined as inacceptable, risk reduction measures must be implemented *"irrespectively of the costs"* in order to reach the acceptable risk (Skjong, 2002). Second, the negligible region is where the risk is insignificant by most peoples' standards, and corresponds to one order of magnitude below the average acceptable risk. In the literature, there is no consensus on actions required for the risk within this region, as some advocate for no action (Det Norske Veritas, 2001), others for decisions based on cost-effectiveness analysis (Coile et al., 2019). Finally, the ALARP region is where the risk is tolerable or acceptable. In this region, solutions to reduce the risk can be adopted on the condition that *"their burden (in terms of cost, effort or time) is not grossly disproportionate to the reduction in risk that they achieve"* (Det Norske Veritas, 2001).

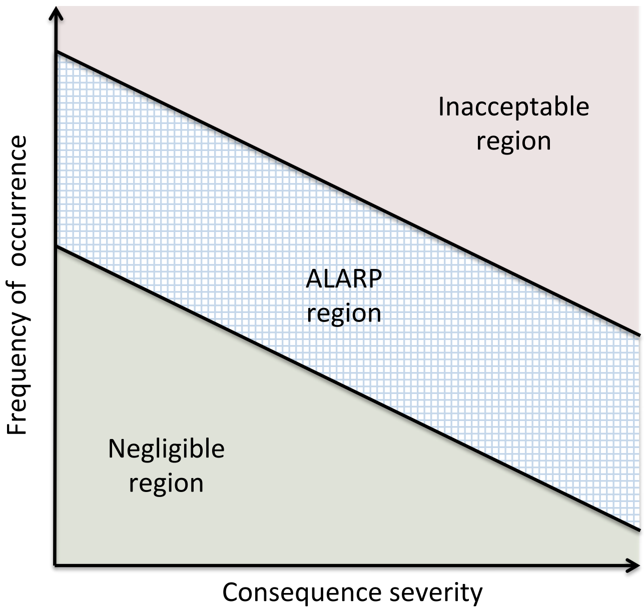

Figure 29. Illustration of the ALARP approach. Conception: Sèbe from Coile et al., 2019.

For whale conservation, the approach dealing with risk is more heterogeneous. The notion of acceptable risk appears in the Revised Management Procedure of the IWC guidelines for whaling. In these guidelines, the acceptable risk corresponds to a removal threshold that does not seriously increase the risk of extinction (Aldrin et al., 2009) In addition to the IWC guidelines, the notion of acceptable risk was also discussed during a NOAA workshop (Angliss et al., 2002). In this workshop, the acceptable risk was described as one of the five recovery criteria to define the level of threat to a population. It was defined that a species should be designated as endangered, according to the U.S. Marine Mammal Protection Act (U.S. MMPA), if the probability of becoming extinct is greater or equal to 1% in 100 years. The International Union for Conservation of Nature (IUCN) criterion follows the same principle, but the acceptable risk varies from the U.S. MMPA (Angliss et al., 2002; De Grammont and Cuarón, 2006). While some recommendations were emitted for dealing with acceptable risk (e.g., time frame, population units) during the NOAA workshop, few academic studies have stemmed from this workshop. Nowadays, the most practical tools, in relation to acceptable risk, are the management rules. Management rules are conservation targets that influence policy decisions (Chapter 4; Lonergan, 2011; Barlow et al., 1995; IWC, 1999b). Several types of management rules exist (e.g., Potential

Biological Removal, Critical Reference Point, IWC Revised Management Procedure, HELCOM), some more complex than others (Curtis et al., 2015), and aiming at different objectives of recovery.

Conservationists and the shipping industry approach the notion of acceptable risk differently. Most of the time, conservationists do not propose a full estimation of the risk. Although, the definition of the risk of collision hot spots through modeling is well-illustrated in the literature (Martin et al., 2015; Rockwood et al., 2017; Vanderlaan et al., 2008a), as expressed in Chapter 1 and 4, the severity – consequence – of this risk is rarely defined at the population level (Brown et al., 2019). In other words, if a conservationist says that collisions kill ten whales per year in a given area, the shipping industry might ask if it is a lot, and the conservationist would generally not be able to answer quantitatively (Brown et al., 2019). Besides, even in cases where the conservationists propose such an answer, by comparing the risk with management rules, an issue with the risk variability arises; the solutions that would be needed to reach management rules may be too drastic for the shipping industry. As observed in Chapter 4, in the case of the fin and sperm whales, the Potential Biological Removal (PBR) is too low to be reachable, given the level of the shipping industry activity.

Consequently, further research is required in order to align the industry and conservation acceptable risk processing. Based on the NOAA workshop and the ALARP approach, studies may investigate, for example, to fix conservation unacceptable risk as the upper boundary of the ALARP region by using the PBR (Chapter 4). For the lower boundary, the Critical Reference Point (CRP) could be used. This way, the shipping industry would be presented with an acceptable range of risk for conservation, and would have more flexibility. This might lead to higher compliance towards conservation targets (Angliss et al., 2002; Mace et al., 2008; Vanem, 2012). To be noted that the shipping industry would have to rely on an *"individual human-based approach to risk"* for environmental issues, such as whales. Still, at least, conservationists and industry stakeholders would speak the same language.

3.2.2. THEORETICAL EFFECTIVENESS, EFFICIENCY, AND APPPLIED EFFECTIVENESS

Conservationists should integrate the notion of theoretical effectiveness, efficiency, and applied effectiveness. Currently, when conservationists propose solutions to mitigate whale-ship collisions, the risk reduction is generally expressed through the theoretical effectiveness (Chapter 1; Guzman et al., 2013; Wiley et al., 2011). The theoretical effectiveness is here defined as the degree to which a solution is effective without constraints; in contrast to the applied effectiveness that does take these constraints into account (e.g., incentive, laws, and logistics). Within the FSA, the cost-effectiveness ratio calculation allows estimating the efficiency of the solutions through a comparison of the theoretical effectiveness with the costs.

Once these ratios are calculated, the shipping industry will most likely choose the most efficient – aka cost-effective – solution (Fig. 30a). At this selection stage, conservationists must be careful to propose solutions that reach conservation targets in terms of risk reduction. For example, between solution A that costs $1,000,000 for a 100% risk reduction (no more risk), and solution B that costs $100,000 for a 10% risk reduction, the shipping industry will choose solution B. Indeed, the two solutions have the same cost-effectiveness ratio ($10,000 per percentage of reduction), but solution B is less expensive (Kontovas, 2005). In this situation, conservationists could propose, for example, a solution C for $700,000 and a 80% reduction ($8,800 per percentage of reduction).

Once the efficiency of a solution is established, as demonstrated in the previous example, the cost of this solution will be the first constraint to explain the difference between theoretical and applied effectiveness. For two solutions with the same cost-effectiveness ratio, and without other constraints (e.g., incentive, regulation, sensitization), the industry compliance will directly be linked to the costs, and define the *slope* of the applied effectiveness *plane* of the solution (Fig. 30b). Other constraints will impact the applied effectiveness, such as, for example, fines for non-compliant companies, which can produce a two-third reduction in the violation rate (Shimshack and Ward, 2005).

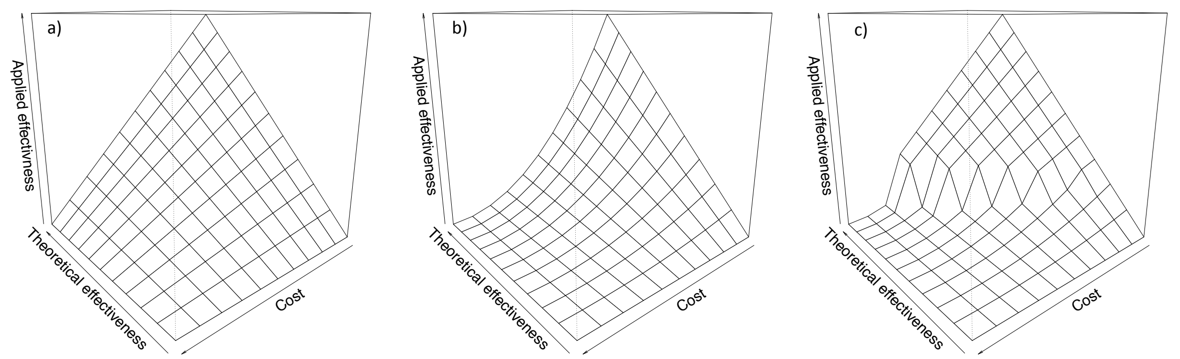

Figure 30. Conceptual illustration of applied effectiveness without (a) with constraints (b), and with the implementation of risk evaluation criterion (c) depending on cost and theoretical effectiveness. Without constraints, the applied effectiveness is directly linked to the efficiency of the solution (a). With the constraints – here, the hypothetical proportionality between cost and compliance – the applied effectiveness is lower, especially for more expensive solutions (b). The implementation of the risk evaluation criterion will temper the impact of the cost on the compliance, especially for more expensive solutions (c), and then improve the applied effectiveness. Conception: Sèbe.

In the FSA, we apply a positive constraint to the applied effectiveness by defining the risk evaluation criterion. This criterion acts as a societal safety requirement by establishing a lower boundary to a private analysis (Coile et al., 2019). If during the cost-effectiveness analysis, the cost outweighs the benefit, the criterion defines if the cost is disproportionate in comparison to the risk reduction induced (Skjong, 2002). Hence, the risk evaluation criterion will allow the recommendation of a relatively expensive solution by the IMO decision-makers. The IMO recommendation will then improve the shipping company compliance with the solution, and the applied effectiveness of it, especially for expensive-efficient solutions (Fig. 30c). The criterion adds a positive constraint that increases the compliance, and then the applied effectiveness, as illustrated in Figure 30c with a variation of the *slope* of the applied effectiveness *plane*.

Further research is also needed not only to define a *"whale"* risk evaluation criterion better, but also to investigate the need for options other than this criterion. Our approach needs to be refined, as some limitations to our assumptions have been shown in the literature (e.g., non-linearity, double counting; Kontovas and Psaraftis, 2008; Kontovas, 2011; Psaraftis, 2008). Also, the use of the existence value, as shown in Chapter 5, can be questioned (Babcock, 2013), and other ways of decision-making can be investigated, for example, though ecosystem services (Cook et al., 2020; Riisager-Simonsen et al., 2020). However, as explained in Chapter 5, the ecosystem service approaches so far fail to encompass the severity of an individual whale removal. Indeed, the impact of the removal of one individual from a whale population for the related ecosystem services is low, whereas its impact can be significant for the whale population.

More broadly, the integration of the notions of efficiency, theoretical, and applied effectiveness can be decisive not only for the shipping industry, but also for conservationists if they wish to reach whale conservation targets (Constantine et al., 2015; B. Czech, 2000; O'Brien, 2006).

3.2.3. SYSTEMIC APPROACH BEYOND THE FORMAL SAFETY ASSESSMENT

The FSA provides a framework for a systemic approach, but I advocate for the development of a similar approach beyond the scope of the FSA. For example, proposals to the IMO Marine Environment Protection Committee (MEPC) could integrate logistic and economic aspects, which are sadly missing in the current whale-related proposals. By using the FSA reasoning in proposals to the MEPC, the submitter may overcome some limitations of the FSAs and current proposals, and will provide the IMO with the required information for decision-making (IMO, 2016a, 2012a). Similarly, to overcome the transboundary issue of whale management, initiatives to implement Particularly Sensitive Sea Areas (PSSA) are considered (IMO, 2016a). As a reminder, a PSSA is *"an area that needs special protection through action by IMO because of its significance for recognized ecological, socio-economic, or scientific attributes where such attributes may be vulnerable to damage by international shipping activities"*. Within PSSAs, mitigation solutions can be designated, and a proposal including a systemic approach may increase its transparency, and, therefore, its acceptance. Such an approach may lead to effective governance, which is the key driver for future environmental states (De Menthière et al., 2016; Lacroix et al., 2019).

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ANNEXES

ANNEX 1 – TREATIES, CONVENTIONS, AND AGREEMENTS FOR WHALE'S PROTECTION

Table A1. List of the Treaties, Conventions, and Agreements for whale's protection.

Year of adoption	Name of treaty, convention, agreement	Area of coverage
1946	ICRW - International Convention for the Regulation of Whaling (convention responsible for establishing the International Whaling Commission - IWC)	World ocean: high seas
1952	PCSP - Permanent Commission and Agreements of the Conference on the Use and Conservation of the Marine Resources of the South Pacific	South Pacific: national waters to EEZ limits and high seas
1968	UNESCO Man and the Biosphere Programme (MAB)	World ocean: national waters to EEZ limits and possibly high seas
1971	Ramsar - Convention on Wetlands of International Importance Especially as Waterfowl Habitat	World ocean: inshore portions of national waters only
1972	World Heritage Convention (WHC) - Convention Concerning the Protection of the World Cultural and Natural Heritage	World ocean: national waters to EEZ limits and high seas
1973	CITES - Convention on International Trade in Endangered Species of Wild Fauna and Flora	World ocean: national waters to EEZ limits and high seas
1973	MARPOL Agreement - International Convention for the Prevention of Pollution from Ships put into practice by IMO (International Maritime Organization)	World ocean: national waters to EEZ limits and high seas
1974	UNEP (United Nations Environment Programme) Regional Seas Programme	Individual regions of the world, typically national waters and high seas
1975	Barcelona Convention - Convention for the Protection of the Mediterranean Sea Against Pollution	Mediterranean: national waters (declared only to 12nm with some exceptions) and high seas
1976	CNSP - Convention on Conservation of Nature in the South Pacific	South Pacific: national waters to EEZ limits and possibly high seas
1978	Kuwait Convention - Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution (ROPME)	Persian Gulf including national waters of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates
1978	NAFO - Northwest Atlantic Fisheries Organization and Convention on Future Multilateral Cooperation in the Northwest Atlantic Fisheries	Northwest Atlantic: national waters to EEZ limits and high seas
1979	Bern Convention - The Emerald Network; Convention on the Conservation of European Wildlife and Natural Habitats	European seas: national waters to EEZ limits (declared and undeclared)
1979	CMS or Bonn Convention - Convention on the Conservation of Migratory Species of Wild Animals	World ocean: national waters to EEZ limits and high seas
1980	CCAMLR - Convention on the Conservation of Antarctic Marine Living Resources	Antarctic: high seas
1981	Abidjan Convention - Convention for Cooperation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region	West Africa
1982	Jeddah Convention - Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment	Red Sea and Gulf of Aden
1982	UNCLOS - United Nations Convention on the Law of the Sea: General provisions	World ocean: national waters to EEZ limits and high seas
1982	UNCLOS: Environment Regime	World ocean: national waters to EEZ limits and high seas

1982	UNCLOS: Fisheries Regime	World ocean: national waters to EEZ limits and high seas
1983	Cartagena Convention (Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region) and the Protocol Concerning Specially Protected Areas and Wildlife (SPAW)	Greater Caribbean Sea: national waters to EEZ limits and high seas
1985	Nairobi Convention or MCEA - Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region	East African and western Indian Ocean countries: national waters to EEZ limits and possibly high seas
1986	Lima Convention or CPPS - Convention for the Protection of the Marine Environment and Coastal Area of the South-East Pacific	Southeast Pacific: national waters to EEZ limits and possibly high seas
1986	Noumea Convention - Convention for the Protection of the Natural Resources and Environment of the South Pacific Region	Pacific Islands Region: national waters to EEZ limits and high seas
1991	ASCOBANS - Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas	Baltic and North seas, Western European seas: to EEZ limits
1992	Bucharest Convention - Convention on the Protection of the Black Sea Against Pollution	Black Sea: national waters to EEZ limits and high seas
1992	EU Habitats Directive (Natura 2000)	EU waters: national waters to EEZ limits
1992	HELCOM or Helsinki Convention - Convention on the Protection of the Marine Environment of the Baltic Sea Area	Baltic Sea: national waters to EEZ limits and possibly high seas
1992	United Nations Conference on Environment and Development (UNCED): Agenda 21	World ocean: national waters to EEZ limits and high seas
1994	CBD - Convention on Biological Diversity and the Jakarta Mandate	World ocean: national waters to EEZ limits and high seas
1995	SPA Protocol - Protocol Concerning Specially Protected Areas and Biological Diversity of the Barcelona Convention	Mediterranean: national waters (declared only to 12nm) and high seas
1996	ACCOBAMS - Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area	Mediterranean and Black seas: national waters (declared only to 12nm with some exceptions) and high seas
1998	OSPAR Convention - Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic	Northeast Atlantic Ocean: EEZs and high seas
2001	United Nations Agreement on Straddling Fish Stocks (1995)	World ocean: national waters to EEZ limits and high seas
2002	World Summit on Sustainable Development (WSSD): Plan of Implementation	World ocean: national waters to EEZ limits and high seas
2006	Pacific Cetaceans MoU - Memorandum of Understanding for the Conservation of Cetaceans and Their Habitats in the Pacific Islands Region	Pacific Islands Region: national waters to EEZ limits and high seas
2008	WATCH - Memorandum of Understanding Concerning the Conservation of the Manatee and Small Cetaceans of Western Africa and Macaronesia	West Africa and Macaronesia: national waters to EEZ limits

ANNEX 2 – WHALE-SHIP COLLISION: A BIBLIOMETRIC STUDY

Various solutions to avoid whale collision are discussed in the literature. These studies are rarely as complete as the one we can find on land studies, e.g., on wildlife-car collisions. Indeed, if recurrent parameters are discussed in the literature, they are rarely discussed at the same time. A bibliometric analysis was performed to highlight the lack of an interdisciplinary approach in whale collision literature.

METHOD

Selection of articles

The following rules were applied to the analysis:

1) Selected articles only related to the collisions. Multi-threat articles were excluded.

2) The attribution of a parameter to an article was made if an article brought new information to the subject about this parameter. Exceptions were made when new information was brought to a parameter using old information from another parameter originating from another article. In this case, the two parameters were attributed to the article because of the interdisciplinary approach.

3) The time scope of the study was from January 2000 to March 2018.

Selection of parameters

Table A2. Bibliometric parameters used for the literature review.

Parameter code	Parameter	Definition	Examples
P1	Collision assessment	Parameter includes articles studying the actual risk of collision, either through ship traffic vs. whale density models or through the assessment of the number of deaths (e.g., stranding) or injured whales (through photo-identification).	(Berman-Kowalewski et al., 2010; Félix and Van Waerebeek, 2005; Knowlton and Kraus, 2001)
P2	Solutions	Parameter includes articles studying the implementation of a solution to avoid whale collisions. Any article discussing (and not just mentioning) a solution can belong in this parameter, even if they do not provide information on the other parameters (P1, P3, P4, P5, P6)	(Delory et al., 2007; Guzman et al., 2013; Mullen et al., 2013)
P3	Risk reduction	Parameter includes articles studying the risk reduction of a solution.	(Merrick and Cole, 2007; Parrott et al., 2016; Wiley et al., 2011)
P4	Cost and Benefit	Parameter includes articles studying the cost and benefit of a solution.	(Kite-Powell, 2005; Kite-Powell and Hoagland, 2002; Nathan Associates Inc, 2012)
P5	Voluntary or Mandatory	Includes articles studying the voluntary or mandatory implementation of a solution.	(Freedman et al., 2017; Laist et al., 2014; Silber et al., 2015)
P6	Compliance	Articles studying the compliance or the willingness to act of the shipping industry.	(Silber et al., 2014; Silber and Bettridge, 2012; Silber and Wallmo, 2017)

RESULTS

Selected articles

A total of 222 articles were extracted from the Scopus database. Each article was studied in order to identify their contribution to the parameters. Some relevant *"grey literature"* were added. Given the broad scope of key-words chosen and the strict rules of the study, the false positive rate was high (45%) and only 99 articles were included for analysis.

Connectivity between parameters

Of the 99 articles selected, nearly half addresses only one parameter. The proportion of articles addressing 2 or 3 parameters is also high (see Fig. 10 in Introduction; Fig. A1). On the contrary, articles that address more than 3 parameters are in the minority (10%).

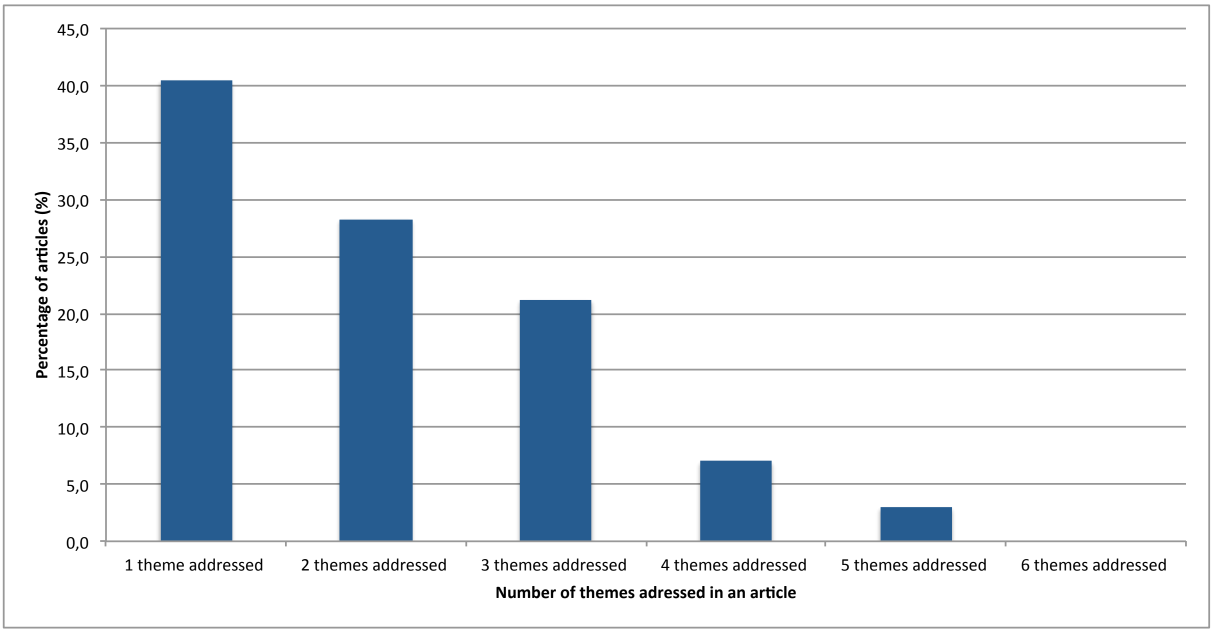


Figure A1. Proportion of themes processed in the literature. Conception: Sèbe.

Table A3. Distribution of the whale-ship collision literature.

Geographic area	Percentage of papers in the literature review (%) (N=107)
Alaska	7
Arctic	1
Australia	1
Bay of Biscay	1
Brazil	1
Canadian Arctic	2
Canadian East Coast	7
Canadian West Coast	3
Canary Islands	4
Hawaii	1
Mediterranean	1
New Zealand	1
Russia	1
Southern Hemisphere	1
Sri Lanka	2
US East Coast	36
US West Coast	7
West Coast Panama	1
Western Mediterranean	10
World	12

ANNEX 3 – WHALE-SHIP COLLISION DYNAMIC AND MANAGEMENT – SHORT COMMUNICATION

Author: Maxime Sèbe, Sophie Gourguet.

Draft: 11/06/20

Abstract: Much could be learned from aviation for whale-ship collision management

Marine giants, especially whales, participate in human well-being through primary production, nutrient cycling, carbon sequestration, recreation, and education (Cook et al., 2020). However, human activities threaten whale survival. Populations of whales are facing indirect human impacts such as ocean noise and pollution, but also direct impacts such as whaling, fishing gear entanglements, and collisions with ships (Kraus, 2005; Thomas et al., 2016).

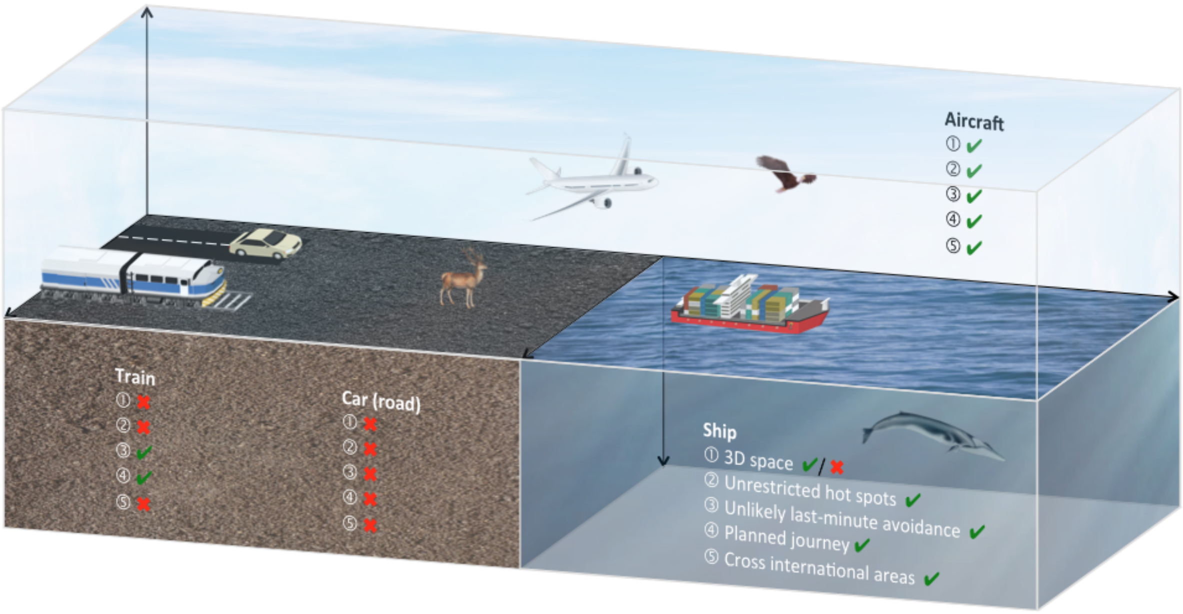
Whale-ship collisions – which can be lethal for these marine mammals (Thomas et al., 2016)– could be avoided, but the lack of a holistic approach in risk assessment jeopardizes the implementation of effective management measures by maritime industries. With maritime traffic expanding, this threat can be expected to increase. It is therefore pivotal to investigate what can be learned from other transportation modes in order to mitigate these impacts and improve whale conservation.

Shipping routes have recently been compared to terrestrial roads, where concepts from terrestrial road ecology have been borrowed to assess the direct and indirect ecological impacts from shipping on marine giants (Pirotta et al., 2019). We extend, here, this original approach to compare the features and the management of collision with wildlife in maritime and aviation industries that might be a best-suited comparison given the dimension governing the collision dynamics.

The encounter space between whales and ships can be compared to the three-dimensional (3D) space governing wildlife-aircraft collisions. While a marine vessel operates mainly in a two-dimensional (2D) plane, part of it is in the 3D space inhabited by whales. The ship draught can reach a depth of ca. 25 meters, depending on the ship size and category, and some species of whales spend a considerable amount of time at these depths (e.g., Bryde's whales in the Hauraki Gulf spend 91% of their time between 0 and 14m; (Constantine et al., 2015)). Though this 3D environment, theoretically, allows individuals to fly (aerial realm) or dive (marine realm) to avoid being hit, this environment characteristic also hinders the detection of birds (for aircraft) or whales (for ships); the speed and manoeuvrability of airplanes and ships lower the animal detection possibilities and prevent adapted last-minute avoidance reactions.

Aerial and maritime transportation journeys are both planned, which allow modeling the probability of a collision with reasonable confidence. However, airways and marine roads are not marked by physical materials, such as asphalt or rails; consequently, hot spots of collisions are not contained to a small piece of land, but span broader areas. In addition to these characteristics (3D space, unlikely last-minute avoidance, planned journey, unrestricted hot spots), aircrafts and ships cross international borders. These vehicles might, therefore, be bound to different regulations over the course of their journey, which makes management challenging.

Despite these similarities between wildlife-aircraft and whale-ship collision features, primary motivations to avoid these collisions are utterly different, resulting in contrasted management processes. On one hand, as bird strikes can be fatal for those on board a plane, the primary concern in aerial collisions is the safety of the crew and passengers. This human safety consideration engaged the aviation into standardization processes over the last decades (Devault et al., 2009). Wildlife-aircraft collision management follows a top-down process supervised by the International Civil Aviation Organization (ICAO), which manages wildlife-aircraft collisions at the international level since the 1990s. The ICAO is a United Nations Agency *"whose mission is to achieve safe, secure, and sustainable development of civil aviation"*. This agency manages a global strike database, encourages strike reporting, and advocates for risk assessment and cost-effectiveness analysis, through internal standardized processes (Anderson et al., 2015; ICAO, 2017a). Thanks to the extensive analysis of databases, the wildlife-aircraft collision management is now composed of proactive solutions (e.g., airport selection, seasonal adaptation, compensation (Devault et al., 2009)). On the other hand, environmental concerns prevail for whale-ship collisions, as safety issues and property damages are deemed low (Sèbe et al., 2020). Consequently, few standardized processes have emerged, and whale-ship collision management follows a bottom-up process. When a hot spot of collisions is identified, solutions are proposed at the regional level, most of the time, without any complete risk assessment, or cost-effectiveness analysis (Sèbe et al., 2020). Sometimes, these mitigation solutions are submitted to the International Maritime Organization (IMO; (G. K. Silber et al., 2012)), which is the maritime counterpart of the ICAO. However, these proposals are generally only accepted if the submitting country has already implemented the solutions at the national level. Otherwise, these proposals are often rejected due to the lack of a holistic approach integrating costs, benefits, and induced reduction of risks, which prevents IMO members from making a decision (Sèbe et al., 2020; G. K. Silber et al., 2012).



Comparison of the main features of wildlife-vehicle collisions between four transportation industries. Whale-ship collisions share more characteristics with wildlife-aircraft collisions than with terrestrial wildlife-vehicle collisions. Conception: Sèbe, Guillou and Gourguet

As proactive actions are crucial to prevent animal losses (D. J. McCauley et al., 2015), much could be learned from the ICAO standardized management process for aviation. For whale-ship collision management, the lack of a top-down process, an extensive global strike database, and standardized protocols often leads to a low level of compliance with suggested mitigation measures. If the same regional rules – such as speed reduction or areas to be avoided – were applied at the international level, as it has been punctually done, it would reduce competition among shipping companies, and therefore increase their willingness to act. Furthermore, as compliance markedly increases with regulation (McKenna et al., 2012; Vanderlaan and Taggart, 2009), these companies would be more likely to comply with measures aiming at mitigating their impacts on whales.

Lessons learned by IMO from ICAO would not only reduce threats on whales, but also prevent further damages and bad publicity for shipping companies (Sèbe et al., 2020). Entering port with a 14-meter-long dead fin whale draped over the bow bulb of a ship is poor advertising; yet the image of shipping companies is crucial for their prosperity. While incentives for the maritime industry might not be linked to damage costs or human safety, it is in their best interest to preserve whales by reducing collisions.

While the International Whaling Commission (IWC) or local initiatives are needed to manage pressing collision matters – such as the one related to the conservation of endangered whale species – we recommend that IMO gets more involved in the long-term and international management of whale-ship collisions. If it doesn't, the long-term survival of some whale populations is at risk.

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ANNEX 4 – WHALE-SHIP COLLISION HAZARD LIST

Table A4. Hazard list to be vetted by the focus group experts.

Factors	Hazard Type	Hazard	Source
Cont.Event.1.Visual detection failure			
Human Factors	Detection Competence / Capacity	Failure to identify visually a Unidentified Floating Object (UFO)	Mayol, 2007; Silber, Bettridge and Cottingham, 2009; Weinrich, Pekarcik and Tackaberry, 2010; Arcangeli et al., 2012; Silber and Bettridge, 2012; Couvat and Gambaiani, 2013; Lloyd's Register, 2015
Human Factors	Detection Competence / Capacity	Failure to identify visually a whale	Mayol, 2007; Silber, Bettridge and Cottingham, 2009; Weinrich, Pekarcik and Tackaberry, 2010; Arcangeli et al., 2012; Silber and Bettridge, 2012; Couvat and Gambaiani, 2013; Lloyd's Register, 2015
Human Factors	Detection Competence / Capacity	Inattention (multitasking/too much information/too many activities/fatigue…)	Mayol, 2007; Silber, Bettridge and Cottingham, 2009; Weinrich, Pekarcik and Tackaberry, 2010; Arcangeli et al., 2012; Silber and Bettridge, 2012; Couvat and Gambaiani, 2013; Lloyd's Register, 2015
Human Factors	Detection Competence / Capacity	Lack of watch	Varin, comm. pers.
Human Factors	Detection Competence / Capacity	Lack of training to detect whale	Varin, comm. pers.
Environmental	Season	Whale density and species vary in function of seasons	Mayol, Capoulade and Beaubrun, 2007; Silber, Bettridge and Cottingham, 2009; Arcangeli *et al.*, 2012; Williams *et al.*, 2016
Environmental	Area	Whale density and species vary in function of areas	Mayol, Capoulade and Beaubrun, 2007; Silber, Bettridge and Cottingham, 2009; Arcangeli *et al.*, 2012; Williams *et al.*, 2016
Environmental	Whale activity	Whale activity influence visual detection (Blow/dive with no fluke/Dive with fluke/Lunge feeding/Resting/Surface activity)	Williams *et al.*, 2016
Environmental	Climatic condition	Rain - Affect visual detection	Mayol, Capoulade and Beaubrun, 2007; Arcangeli *et al.*, 2012; Lloyd's Register, 2015; Williams *et al.*, 2016
Environmental	Climatic condition	Haze - Affect visual detection	Mayol, Capoulade and Beaubrun, 2007; Arcangeli *et al.*, 2012; Lloyd's Register, 2015; Williams *et al.*, 2016
Environmental	Climatic condition	Sun - Affect visual detection	Varin, comm. pers.
Environmental	Climatic condition	Night - Affect visual detection	Seguinot, Varin, comm. pers.
Environmental	Climatic condition	Swell - Affect visual detection	Mayol, Varin, comm. pers.
Environmental	Climatic condition	Wind - Affect visual detection	Mayol, Capoulade and Beaubrun, 2007; Arcangeli *et al.*, 2012; Lloyd's Register, 2015; Williams *et al.*, 2016; Varin, comm. pers.
Cont.Event.2. Human avoidance failure			

Human Factors	Avoidance Competence / Capacity	Hierarchical unwillingness to speak up, power distance gap	Lloyd's Register, 2015
Human Factors	Avoidance Competence / Capacity	Multitasking: Too many activities, leading to a loss of focus on high priority tasks	Lloyd's Register, 2015
Human Factors	Avoidance Competence / Capacity	Lack of training to avoid (depending on the whale behavior)	Lloyd's Register, 2015; Varin, Capoulade, Roubaud, comm. pers.
Cont.Event.3.Ship technology detection failure			
Shipboard Technology	Electronic charts	Whale not reported on the REPCET interface (not reported or REPCET bug)	Seguinot, Roux, Mayol, comm.pers
Cont.Event.4.Ship technology avoidance failure			
Shipboard Technology	Mechanical failure	Inability to execute manoeuvre (Steering System Failures (rare) or Complete Black-out (electronic issue))	Lloyd's Register, 2015
Shipboard Technology	Ship type and equipment	Ship speed	Varin, Capoulade, Roubaud, comm. pers.
Shipboard Technology	Ship type and equipment	Turn radius	Varin, Capoulade, Roubaud, comm. pers.
Cont.Event.5.Detection and avoidance failure due to situational characteristics			
Physical surrounding	Density of maritime traffic	Density of mixed ship (some without VTS) provides a safe avoidance	Martins and Maturana, 2013; Akten, 2004; Ngarajan et al., 2008; Lloyd's Register, 2015.
Physical surrounding	Density of maritime traffic	Congestion of the traffic	Martins and Maturana, 2013; Akten, 2004; Ngarajan et al., 2008; Lloyd's Register, 2015.
Physical surrounding	Limited sea room	Choke points, Close proximity of anchorages and harbor areas, Proximity of navigational hazards (e.g., shoal)	Martins and Maturana, 2013; Akten, 2004; Ngarajan et al., 2008; Lloyd's Register, 2015.
Policies	Regulatory framework	Marine safety information	Roubaud, Capoulade, Mayol, Varin, comm. pers.
Policies	Regulatory framework	Navigational rules (COLREG)	Roubaud, Capoulade, Mayol, Varin, comm. pers.
Policies	Regulatory framework	TSS & Precautionary area	Roubaud, Capoulade, Mayol, Varin, comm. pers.
Cont.Event.6.Avoidance and detection failure due to commercial constraint			
Internal functioning	Commercial pressures	Avoidance of a whale area will increase fuel consumption	Lloyd's Register, 2015
Internal functioning	Commercial pressures	Pressures to make ETAs, others	Lloyd's Register, 2015
Policies	Other environmental stakes	Gaseous pollutants (e.g., ECA, SECA)	Seguinot, Mayol, comm.pers
Policies	Regulatory framework	Inadequate, misunderstood, unforced regulatory framework	Lloyd's Register, 2015

ANNEX 5 - CHAPTER 3 SUPPLEMENTARY INFORMATION

Table A5. Mixed logit results with only significant parameters ((M1.a) Independent) and results of resampling with only captains, only cargo, or only with respondents that gave no answer below 3 at the Likert scale. Abbreviations: TD = Travel distance; TRI = Time of reception of the information; AOI = Area of interest; AS = Avoidance solution; SRS = Speed reduction solution.

	ML with only significant parameters		ML with only significant parameters, only captains		ML with only significant parameters, only cargo		ML with only significant parameters, only Lickert scale Attendance >3	
Attributes	(M1.a) Independent		(M1.a) Independent		(M1.a) Independent		(M1.a) Independent	
	$\hat{b}$	$\hat{\sigma}$	$\hat{b}$	$\hat{\sigma}$	$\hat{b}$	$\hat{\sigma}$	$\hat{b}$	$\hat{\sigma}$
	(pvalue)	*(pvalue)*	*(pvalue)*	*(pvalue)*	*(pvalue)*	*(pvalue)*	*(pvalue)*	*(pvalue)*
TD	0.00169	0.00261	0.00210	-0.00195	0.00166	0.00261	0.00113	0.00277
	(0.00145)	(1.24e-05)	(0.00409)	(0.0490)	(0.0108)	(0.000803)	(0.211)	(0.00585)
TRI	0.141	0.0594	0.112	0.0830	0.135	0.0652	0.0983	-0.0488
	(7.98e-05)	(0.000250)	(0.0398)	(0.00114)	(0.00321)	(0.00176)	(0.0774)	(0.0498)
TRI^2	-0.00464		-0.00399		-0.00457		-0.00250	
	(0.000638)		(0.0530)		(0.00892)		(0.235)	
AOI	-0.0700	0.0584	-0.0891	-0.0775	-0.0865	-0.0420	-0.0591	0.0135
	(1.82e-05)	(0.00945)	(0.000530)	(0.0382)	(5.86e-06)	(0.164)	(0.00923)	(0.832)
AS (coding effect)	0.391	-0.653	0.354	0.445	0.466	0.710	0.315	0.657
	(0.00255)	(1.59e-05)	(0.0452)	(0.0268)	(0.00626)	(0.000229)	(0.128)	(0.00895)
SRS	0.0740	0.0863	0.0236	0.0665	0.0672	0.0988	0.0989	0.106
	(0.00196)	(1.20e-09)	(0.469)	(0.000231)	(0.0299)	(4.70e-07)	(0.0227)	(4.69e-05)
SRS^2	-0.00310		-0.00176		-0.00283		-0.00336	
	(4.05e-07)		(0.0378)		(0.000176)		(0.000810)	
Observations	1608	1608	720	720	1104	1104	672	672
n	67	67	30	30	46	46	28	28
AIC	977.5	977.5	449.4	449.4	666.3	666.3	402.3	402.3
BIC	1042	1042	504.3	504.3	726.4	726.4	456.4	456.4
K	12	12	12	12	12	12	12	12
LIK	-476.8	-476.8	-212.7	-212.7	-321.1	-321.1	-189.1	-189.1

ANNEX 6 – CHAPTER 4 SUPPLEMENTARY INFORMATION

BIBLIOMETRIC STUDY PARAMETERS

Given the variability of the population-level data for the Mediterranean sub-populations (Mannocci et al., 2018), a literature review was performed to identify Mediterranean whale sub-population parameters to be used in Chapter 4. The descriptive results of the bibliometric studies, achieved on Scopus, are expressed in the following tables:

Table A6. Descriptive results of the bibliometric study on fin whale life parameters.

Keywords group 1	Keywords group 2	Keywords group 3	Number of publication
"Survival rate*"	"fin whale*"	-	4
"Survival"	"fin whale*"	-	13
"Mortality rate*"	"fin whale*"	-	6
"Mortality"	"fin whale*"	-	46
"vital rate*"	"fin whale*"	-	2
		TOTAL	71
	TOTAL WITHOUT REDUNDANCE		56

Table A7. Descriptive results of the bibliometric study on sperm whale life parameters.

Keywords group 1	Keywords group 2	Keywords group 3	Number of publication
"Survival rate*"	"sperm whale*"	-	4
"Survival"	"sperm whale*"	-	32
"Mortality rate*"	"sperm whale*"	-	6
"Mortality"	"sperm whale*"	-	53
"vital rate*"	"sperm whale*"	-	3
		TOTAL	98
	TOTAL WITHOUT REDUNDANCE		81

Table A8. Descriptive results of the bibliometric study on fin whale abundance.

Keywords group 1	Keywords group 2	Keywords group 3	Number of publication
"Abundance*"	"fin whale*"	Mediterranean	28
		TOTAL	28

Table A9. Descriptive results of the bibliometric study on sperm whale abundance.

Keywords group 1	Keywords group 2	Keywords group 3	Number of publication
"Abundance*"	"sperm whale*"	Mediterranean	28
		TOTAL	20

BIBLIOMETRIC STUDY RESULTS

Results of the bibliometric study on abundances and survival rates for the fin and sperm whale species are expressed in the following tables.

Table A10. Mediterranean fin whale abundance estimations in the literature.

Authors/year	Abundance	CV	CI	Area
Aïssi et al., 2008	71			Ligurian Sea Part of Pelagos
Aïssi et al., 2008	60			Strait of Messina
Aïssi et al., 2008	16			Island of Lampedusa
Arcangeli et al., 2017	308			Sardinian–Balearic road
Arcangeli et al., 2017	37			Bonifacio
Arcangeli et al., 2017	51			Tyrrhenian
Forcada et al., 1995	901	0.217		Western coast of Corsica, Sardinia, and Southeast France
Forcada et al., 1996	3,583	0.27	2,130-6,027	Western Mediterranean
Laran et al., 2017	2,500		1,472-4,310	North-western Mediterranean (Summer)
Laran et al., 2017	1,032		462-2,526	North-western Mediterranean (Winter)
Panigada et al., 2011	148	0.274	87-254	Pelagos (Summer)
Panigada et al., 2017	665	0.331	350-1,263	Extended Pelagos + Italy West coast
Laran et al., 2012	2,607			North-western Mediterranean
IUCN assessment	<5,000			Mediterranean basin

Table A11. Mediterranean sperm whale abundance estimations in the literature.

Authors/year	Abundance	CI	Area
Aïssi et al., 2008	30		Ligurian Sea Part of Pelagos
Aïssi et al., 2008	5		Strait of Messina
Aïssi et al., 2008	5		Island of Lampedusa
Laran et al., 2017	369	84-1,691	North-western Mediterranean (Summer)
Laran et al., 2017	565	123-2,653	North-western Mediterranean (Winter)
Lewis et al., 2018	1,842		Mediterranean basin
IUCN assessment	<2,500		Mediterranean basin

Table A12. Fin whale survival rate estimations in the literature (worldwide).

Authors	Survival rate	Variability	Area
Aguilar and Lockyer, 1987	0.88	-	Northeast Atlantic (Portugal)
Arrigoni et al., 2011	0.937	P90=0.001	Mediterranean
Ramp et al., 2014	0.955	CI: 0.936–0.969	Gulf of St. Lawrence; Canada
Rossi et al., 2014	0.94	P90=0.001	Mediterranean
Sampson et al., 1990	0.96	-	Southern Hemisphere
Schleimer et al., 2019	0.946	CI: 0.910–0.967	Gulf of St. Lawrence; Canada
Zanardelli et al. (2011) in Notarbartolo di Sciara et al., 2016	0.88	CI: 0.76–0.94	Mediterranean
Taylor et al., 2007	*0.96*	-	*Natural survival rate*

Table A13. Sperm whale survival rate estimations in the literature (worldwide).

Authors	Survival rate	Variability	Area
Boys et al., 2019	0.95	*CI:* 0.56–0.99	Azores
Boys et al., 2019	0.93	*CI:* 0.74– 1	Azores
Chiquet et al., 2013	0.977	*CI:* 0.939–0.985	Northern Gulf of Mexico
Labadie et al., 2018	0.953	*CI:* 0.890–0.993	Crozet
Labadie et al., 2018	0.924	*CI:* 0.802–0.992	Kerguelen
Whitehead and Gero, 2015	0.9495	*CI:* 0.926–0.978	Caribbean
Taylor et al., 2007	*0.986*	-	*Natural survival rate*

DETAILS ON PARAMETERS USED IN CALCULATIONS

Recovery factor

The recovery factor Fr is used in the PBR calculation (Wade, 1998). *"The use of a recovery factor for endangered species was to allow a small kill while striving to allow recovery from a dangerously low abundance as quickly as possible"* (Taylor et al., 1997). Given the recovery factor definition (Table A14; Taylor et al., 1997), the recovery factor is set at 0.1 for the Mediterranean fin and sperm whales.

Table A14. Standard whales parameters for the recovery factor Fr calculation (Taylor et al., 1997). CV stands for the coefficient of variation. CR, EN, VU, NT, LC and DD stand respectively for Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern and Data Deficient.

	Population trend				
		Trend unknown		Trend increasing	
N_{min} category	Decreasing	Population IUCN status		Population IUCN status	
		CR-EN-VU	NT-LC-DD	CR-EN-VU	NT-LC-DD
N_{min} < 1500	*Fr* = 0.1	*Fr* = 0.1	*Fr* = 0.1	*Fr* = 0.1	*Fr* = 0.1
CV<0,5 AND 1500< N_{min} <5000 OR CV>0,5 AND 1500< N_{min} <7500	*Fr* = 0.1	*Fr* = 0.1	*Fr* = 0.2	*Fr* = 0.1	*Fr* = 0.3
CV<0,5 AND N_{min} >5000 OR CV>0,5 AND N_{min} >7500	*Fr* = 0.1	*Fr* = 0.2	*Fr* = 0.4	*Fr* = 0.5	*Fr* = 0.5

Notes on HIDM/PBR and HIDM/CRP calculation

The calculation of the number of HIDM, the PBR, and the CPR depend on the abundance *N*. When calculating the ration between HIDM and any abundance-based management rule, the parameter for abundance cancels itself out (see HIDM/PBR calculation below). Consequently, we can assess the severity of HIDM with management rules even without accurate abundance estimations. Stranding data are therefore the most crucial variables for defining the severity of the HIDM on the sub-populations.

$$
\begin{aligned}
\frac{HIDM}{PBR} &= \frac{M_{tot_{strand}} - M_{nat_{strand}}}{\alpha} \times \frac{1}{N\ {}^{1}\!/_{2}\, R_{max}\, F_r} \\
&= \frac{M_{tot_{strand}} - M_{nat_{strand}}}{\frac{M_{nat_{strand}}}{M_{nat_0}}} \times \frac{1}{N\ {}^{1}\!/_{2}\, R_{max}\, F_r} \\
&= \frac{M_{tot_{strand}} - M_{nat_{strand}}}{\frac{M_{nat_{strand}}}{\cancel{N}(1 - s_0)}} \times \frac{1}{\cancel{N}\ {}^{1}\!/_{2}\, R_{max}\, F_r} \\
&= \frac{(1 - s_0)\left(M_{tot_{strand}} - M_{nat_{strand}}\right)}{M_{nat_{strand}}\ {}^{1}\!/_{2}\, R_{max}\, F_r}
\end{aligned}
$$

ANNEX 7 – FSA COST-BENEFIT ASSESSMENT STEP UNDERLYING THEORIES

This section aims to explore the underlying theories of the FSA Cost-Benefit assessment step, mostly based on the work of Kontovas and Psaraftis (2009), and Zheng (2006). After reviewing the general definitions of cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) – the most used approaches when comparing environment costs and benefits trade-off (Grecu et al., 2018; Huijser et al., 2009a) – we analyse the IMO guidelines for the FSA Cost-Benefit assessment step.

COST-BENEFIT ANALYSIS: GENERAL DEFINITION

The cost-benefit analysis (CBA) is *"a method of evaluating the favorable effects of policy actions and the associated opportunity costs of these actions. It answers the question of whether the benefits are sufficient for the gainers to potentially compensate the losers, leaving everyone at least as well off as before the policy"* (U.S. EPA, 2014). In CBA, the analysis must achieve the following inequality for a risk reduction solution to be recommended:

$$\Delta B > \Delta C \qquad (1)$$

Where ΔB is the benefits associated with the policy action implementation and ΔC is the costs associated with the policy action implementation.

The stages of the CBA are the following (Boardman, 2015): "

- *Stage 1: Definition of the project options to be evaluated ;*
- *Stage 2: Decision on whose costs and benefits are counted for ;*
- *Stage 3: Selection of the measurement(s) and measuring all the costs and benefits ;*
- *Stage 4: Estimation of the outcome of cost and benefits over a relevant time period ;*
- *Stage 5: Conversion of all the costs and benefits into a common currency ;*
- *Stage 6: Discounting the costs and benefits into present value ;*
- *Stage 7: Calculation of the NPV for the project options ;*
- *Stage 8: Performing the sensitivity analyses ;*
- *Stage 9: Recommendations based on the NPV and the sensitivity analysis."*

COST-EFFECTIVENESS ANALYSIS: GENERAL DEFINITION

The cost-effectiveness analysis (CEA) is *"a method of evaluating the costs associated with obtaining an additional unit of an environmental outcome. It is designed to identify the least expensive way of achieving a given environmental quality target, or the way of achieving the greatest improvement in some environmental target for a given expenditure of resources"* (U.S. EPA, 2014). As expressed by Nathwani, Lind and Pandey (1997), the CEA is a way to express *"what is the level of expenditure beyond which it is no longer justifiable to spend resources in the name of safety"*. In CEA, the implemented solutions are compared based on the cost (or the net cost) and the effectiveness. One way to compare these solutions is to use the Incremental Cost-Effectiveness Ratio (ICER):

$$\frac{\Delta C}{\Delta R} \qquad (2)$$

Where ΔC is the costs associated with the policy action implementation, and ΔR is the risk reduction induced by the policy action.

The stages of the CEA are the following (Brouwer and De Blois, 2008): "

- *Stage 1: Identify the environmental objective(s) involved (target situation);*
- *Stage 2: Determine the extent to which the environmental objective(s) is (are) met;*
- *Stage 3: Identify sources of pollution, pressures, and impacts now and in the future over the appropriate time horizon and geographical scale (baseline situation);*
- *Stage 4: Identify measures to bridge the gap between the reference (baseline) and target situation (environmental objective(s));*
- *Stage 5: Assess the effectiveness of these measures in reaching the environmental objective(s);*
- *Stage 6: Assess the direct (and if relevant indirect) costs of these measures;*
- *Stage 7: Rank measures in terms of increasing unit costs;*
- *Stage 8: Determine the least cost way to reach the environmental objective(s) based on the ranking of measures."*

GUIDELINES OF THE FSA COST-BENEFIT ASSESSMENT STEP

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 to 8 March 2002) (IMO, 2002a). For more details information about FSA, the interested reader can refer to Sèbe et al. (2019). The FSA is composed of 5 steps:

- Step 1: Identification of hazards: aims to identify and rank all potential hazardous scenarios, which could lead to the studied accidental event;
- Step 2: Risk analysis: aims to quantitatively measure the probability of occurrence and the potential consequences associated with the studied accidental event;
- Step 3: Risk control options: aims to propose effective and practical RCO that will reduce the risk of the studied accidental event;
- Step 4: Cost-benefit assessment: aims to identify and compare the benefits and costs associated with the implementation of each RCO identified and defined in Step 3;
- Step 5: Recommendations for decision-making: aims to recommend to the relevant decision-makers for safety improvement, taking into consideration the findings during all four previous steps.

According to the FSA guidelines, the Cost-Benefit assessment (Step 4) aims to compare the benefits and costs associated with the implementation of an RCO[44]. The IMO guidelines describe the different stages of this step as follows (IMO, 2018a): "

- *Stage 1: 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*
- *Stage 2: 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;*
- *Stage 3: Estimate the pertinent costs and benefits for all RCOs;*
- *Stage 4: Estimate and compare the cost-effectiveness of each option, in terms of the cost per unit risk reduction by dividing the net cost by the risk reduction achieved as a result of implementing the option;*
- *Stage 5: Rank the RCOs from a cost-benefit perspective in order to facilitate the decision-making recommendations in Step 5."*

The FSA Cost-Benefit assessment should incorporate costs associated with "*operating, training, inspection, certification, decommission, etc.*" and benefits associated with "*reductions in fatalities, injuries,*

[44] Risk Control Option, aka solution in the FSA terminology.

casualties, environmental damage and clean-up, indemnity of third party liabilities, etc. and an increase in the average life of ships" (IMO, 2018a).

GENERAL DEFINITIONS VS. FSA COST-BENEFIT ASSESSMENT GUIDELINES

The FSA Cost-Benefit assessment step guidelines show more similarities with the CEA approach than with the CBA one (Zheng, 2006). In particular, stage 4 of the guidelines requires a comparison of the cost-effectiveness of the different RCOs. A CBA exposes a probability an RCO has to produce net benefits ($\Delta B > \Delta C$) rather than a comparison of the net benefits between the RCOs, or the cost associated with these RCOs (U.S. EPA, 2014). In other words, the CBA does not allow comparison between RCOs, as it does not take into consideration the effectiveness of the RCOs (U.S. EPA, 2014).

Another issue within the description of the FSA Cost-Benefit assessment step revolves around potential benefits to be integrated into the analysis. The benefits listed are internal to the shipping industry (IMO, 2018a). This description would suggest that the FSA Cost-Benefit assessment step is really a private CEA, which would not include the benefits and costs associated with all members of society, as advocated by the underlying CBA theory (Fig. A3; Huysegoms et al., 2018; Zheng, 2006). According to the guidelines, the avoided costs are the only benefits that can be integrated when assessing a mitigation solution (e.g., ship repairs, carcasses management; Couvat et al., 2016; Mayol, 2012; Sèbe et al., 2020; Van Waerebeek and Leaper, 2008)

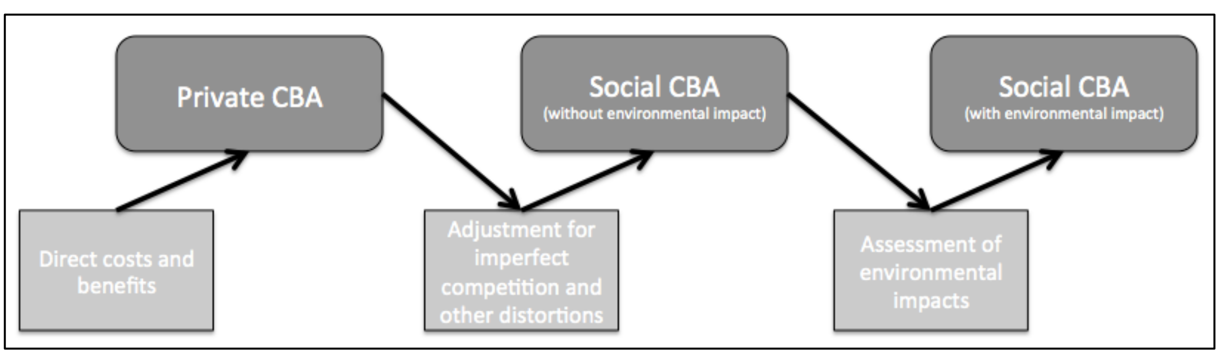

Figure A3. Private to social CBA illustration. Modified from Gouriveau and Robert, 2014. Conception: Sèbe.

Despite guidelines tending toward a private CEA, ways to integrate social benefits have been introduced by the IMO through the implementation of risk evaluation criteria (IMO, 2006b). These criteria are crucial when the costs of implementing a solution are superior to the benefits. In the context of a CBA, the solution would be rejected. However, in a CEA, the costs can outweigh the benefits, and the solution might be accepted depending on a risk evaluation criterion.

To understand this mechanism, one needs to investigate the equilibrium between the FSA ICER and the risk evaluation criterion. Historically, the FSA has been using two ICER – mainly for human safety. The first one is the Gross Cost of Averting a Fatality (GCAF), which only includes the costs associated with the implementation of a human safety RCO. The second one is the Net Cost of Averting a Fatality (NCAF), which integrates the costs and benefits associated with the implementation of a human safety RCO. Sèbe et al. (2019) conceptualized the ICER application for whales in the FSA, by defining the Net Cost of Averting a Whale Fatality (NCAWF). When considering the private aspect of the FSA Cost-Benefit assessment described above, the NCAWF is expressed as follows:

$$NCAWF = \frac{\Delta C_p - \Delta B_p}{\Delta R} \qquad (3)$$

where ΔC_p is the private costs per ship of the RCO under consideration; ΔB_p is the private benefit per ship resulting from the implementation of the RCO; ΔR is the risk reduction induced by the RCO, expressed as the number of whale fatalities averted.

While social benefits do not appear at this stage, some benefits can be integrated into Equation 3. As mentioned before, on one hand, the benefits included in ΔB_p are associated with avoided costs of repairs subsequent to a collision, or the loss of income that resulted from these damages (Sèbe et al., 2020). The avoided cost of carcass management can also be identified, but further researches need to be done, as it is unclear as to who handles these costs (Couvat et al., 2016). On the other hand, conservation benefits are included into ΔR. Indeed, ΔR is expressed here as the number of fatalities avoided, and not as a percentage, which allows calculating the optimal allocation needed to reach conservation targets (Bair et al., 2018). In this case, Population Viability Analysis and Limit Reference Points can be taken into consideration in the CEA (Rose et al., 2015).

Nevertheless, while thanks to the CEA, conservationist can estimate the optimal allocation for conservation, and select the most effective solution in relation to risk reduction induced; it does not help IMO decision-makers, as monetary considerations are a priority in a private CEA. This is why the risk evaluation, also referred as to ICER criterion in the risk assessment terminology, hereafter referred to as *λ,* has been introduced (Fig. A4; Kontovas, 2011; IMO, 2018). This kind of criterion act as a societal safety requirement by establishing a lower bound to private analysis (Coile et al., 2019).

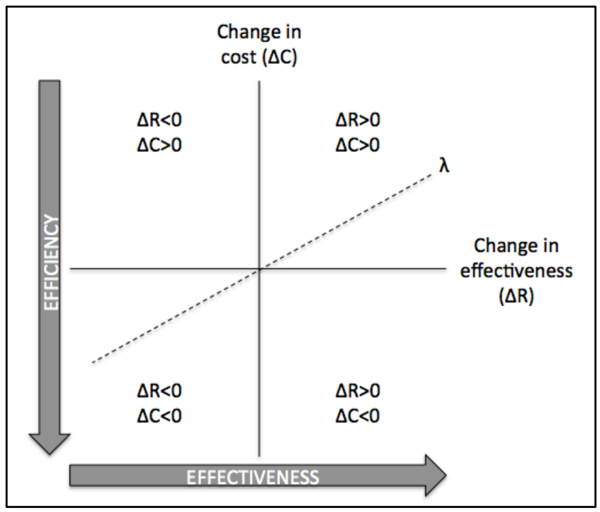

Figure A4. The cost-effectiveness plane and the efficiency associated with it. The trade-off between costs and benefits can be negative (top-right quadrant), but the solutions accepted if below the risk evaluation criterion λ. Modified from Culyer, (2010). Conception: Sèbe.

Derived from the Dictionary of Health Economics (Culyer, 2010), the ICER criterion is here defined as "*the maximum acceptable incremental cost-effectiveness ratio acceptable to decision-maker. Beyond this threshold, the RCO will not be adopted*". In the FSA, this criterion has been express in monetary terms such as dollars per number of fatalities averted or per tonne of pollutant averted (Vanem, 2012). The inequation defining the use of this risk acceptance criterion is the following:

$$NCAWF = \frac{\Delta C_p - \Delta B_p}{\Delta R} < \lambda \qquad (4)$$

If the proposed RCO verify the inequation 4, the RCO is recommended by the IMO; otherwise, it is not. If well-defined, λ can lead toward an equilibrium between CBA and CEA approaches, and integrates the social benefits that could not be monetized in the CBA (Bleichrodt and Quiggin, 1999; Kontovas, 2011). Hence, two options are possible. The first one is when the private benefits to implement an RCO are higher than the private costs, which imply that the private CEA is equivalent to a private CBA (Equation 5). Hence, λ is not needed, as implementing the RCO would improve the company income.

$$\frac{\Delta C_p - \Delta B_p}{\Delta R} < 0 \Rightarrow \Delta C_p - \Delta B_p < 0 \Rightarrow \Delta C_p < \Delta B_p \qquad (5)$$

The second option is when the private benefits are lower than the private costs, and, in this case, the λ needs to be used to integrate social benefits, as expressed in Equation 6.

$$\frac{\Delta C_p - \Delta B_p}{\Delta R} < \lambda \Rightarrow \Delta C_p - \Delta B_p < \lambda\Delta R \Rightarrow \Delta C_p < \lambda\Delta R + \Delta B_p \Rightarrow \Delta C_p < \Delta B_{tot} \quad (6)$$

Where ΔB_{tot} is the total benefit, which is the combination of private and social benefits (that might include double counting). In this case, the integration of λ transforms the private CEA into a social CEA, which tends toward a social CBA (Equation 8 and 9).

Social CEA: $\frac{\Delta C_p - \Delta B_p}{\Delta R} < \lambda \Rightarrow \Delta C_p < \Delta B_{tot}$ (8)

Social CBA: $\Delta C_{tot} < \Delta B_{tot} \Rightarrow \Delta C_p < \Delta C_{tot} < \Delta B_{tot} \Rightarrow \Delta C_p < \Delta B_{tot}$ (9)

According to FSA guidelines (IMO, 2018a), the definition of λ can be achieved through three main methods:

- Observation of the Willingness-To-Pay to avert a fatality (a);
- Observation of past decisions and the costs involved with them (b);
- Consideration of social indicators, such as the Life Quality Index (LQI) (c).

Several λ have been estimated for FSA purposes, but only one seems to have been genuinely accepted at the IMO level: *"the $3m criterion"*. This criterion covers human fatalities from accidents and implicitly, also, injuries or ill health from them. This criterion was inspired by the Life Quality Index and takes into account life expectancy, wealth, and health indicators (Lind, 1996; Nathwani et al., 1997; UNDP, 1990). Researches processing risk acceptance estimated other criterion, which might apply to the FSA (Tab. A15). To be noted that the societal oil spill costs have been integrated into the last FSA guidelines (IMO, 2018a, 2011). Following the Kalder-Hicks theory, while defining a monetary threshold, the compensation is hypothetical (Kontovas, 2011).

Table A15. Existing criterion in the literature. In italic, the ones defined in the literature, but not yet used in an FSA.

Criterion	Value [US $]	Sources
Fatality, injuries and ill health (human)	3 m$	IMO, 2004
Fatality (human)	1.5 m$	IMO, 2004
Injuries and ill health (human)	1.5 m$	IMO, 2004
Oil spill	$ 60,000/tonne	Vanem et al., 2007b, 2008a, 2008b
Carbon dioxide CO_2	*$ 50/tonne*	*Eide et al., 2009 ; Longva et al., 2010*
Nitrogen oxides NO_X	*$ 6,200/tonne*	*Vanem et al., 2011*
Sulfur oxides SO_X	*$ 9,600/tonne*	*Vanem et al., 2011*
Particule matter PM	*$ 31,000/tonne*	*Vanem et al., 2011*

To sum up, the CEA proposed in the FSA allows taking into consideration the social benefits associated with whales by establishing an ICER criterion (λ). This criterion enables transforming the private FSA Cost-Benefit assessment into a social assessment.

CHAPTER 5 - SUPPLEMENTARY MATERIAL

Table A16. Attributes and levels used in the meta-analysis. CV = contingent valuation; CE = choice experiment; GDP PPP = gross domestic product based on purchasing power parity.

Category	Attributes	Levels
Protection objective	Trend	Increase
		No diminution
Study parameters	Study format	Mail
		Face to face
		Internet
		Mixed
		Phone
	Survey mode	CV (
		CE
		Hybrid
	Payment vehicle	Tax
		Trustfund
		Bill
		Unspecified
		Membership
	Payment frequency	Annually
		Monthly
		Once
		Unspecified
	Respondent unit	Per household
		Per person
Site parameters	Income proxy	GDP PPP
Species characteristics parameters	Endangerment status	Endangered
		Not endangered
	Species classification	Marine mammal
		Bird
		Marine fish
		Freshwater fish
		Freshwater mammal
		Diadromous fish
		Marine reptile
		Terrestrial mammal
	Size	Length
		Weight

FRENCH THESIS SUMMARY

FOREWORD

The Doctoral School in Marine and Coastal Sciences requires a minimum of 10 pages' thesis summary in French, as a requirement for submitting an English written thesis manuscript.

Introduction

Les activités humaines menacent la survie de certaines populations de mammifères marins, et notamment des baleines (Thomas et al., 2016). Les menaces peuvent être indirectes (p. ex. pollution, nuisance sonore) ou directes (p. ex. collision avec navire, enchevêtrement dans des équipements de pêches).

Au cours des derniers siècles, deux phases de menaces directes se sont succédées – et superposées (Wang et al., 1994). La première phase est celle d'exploitation. Depuis le 17ème siècle, et jusqu'à 1986, la chasse baleinière commerciale a exploité les stocks de baleines. D'abord stable, cette phase d'exploitation a connu une expansion sans précédent après les guerres mondiales (Rocha et al., 2014). A cette période, certaines populations ont été réduites à 1% de leur abondance d'origine (Clapham, 2016). Après une décennie de négociations (Goodman, 2017), les membres de la Commission Baleinière Internationale (CBI) ont acté, et mis en vigueur en 1986, un moratoire sur la chasse commerciale de la baleine. Aujourd'hui, certains pays continuent la chasse baleinière, mais cette dernière ne représente pas une menace « *active* » pour les populations à l'échelle mondiale (Thomas et al., 2016).

Malgré une tendance positive de certaines populations à la suite du moratoire sur la chasse baleinière, la deuxième phase de menaces a un impact significatif et grandissant sur les populations de baleines. Cette phase se traduit par une mortalité directe non ciblée (Czech, 2000; Czech et al., 2012). Ces mortalités sont les dommages collatéraux de l'interaction directe des baleines avec les secteurs de la pêche (enchevêtrement) et du transport maritime (collision; Thomas et al., 2016). Pour beaucoup de populations, ces deux menaces représentent une grande part de la mortalité induite par l'homme (Ritter and Panigada, 2019).

Les collisions avec les navires – le sujet de cette thèse – représentent l'une des principales menaces modernes à la survie des baleines (Davidson et al., 2012; Ritter et Panigada, 2019). Le risque de collision est créé par la superposition des aires de fortes densités de baleines et des routes maritimes (Campana et al., 2017). La constante expansion du trafic maritime contribue à l'augmentation du risque de collision. La sévérité des blessures des baleines est directement dépendante de la vitesse des navires (Vanderlaan and Taggart, 2007).

Diverses solutions existent pour réduire le risque de collision. Tout d'abord, les solutions opérationnelles rassemblent les mesures qui réduisent le risque en changeant la manière de naviguer des bateaux (Laist et al., 2014). Les principales solutions de ce type sont la réduction de vitesse et l'évitement de zones à risques. Il existe aussi des solutions techniques qui visent généralement à améliorer la détection des baleines (Couvat and Gambaiani, 2013).

Malheureusement, ces solutions, qui sont theoriquement efficaces, sont souvent confrontées au manque de respect des compagnies maritime (p. ex. McKenna et al., 2012). De ce fait, leur efficacité appliquée est généralement limitée (p. ex. Silber and Bettridge, 2012).

Dans le cas des collisions entre véhicules et la vie sauvagess, la gestion de ces événements est différente. Par exemple, les collisions avec les avions affichent une gestion « top-down » standardisée de la part de l'organisation des Nations Unies concernée, à savoir l'Organisation de l'Aviation Civile Internationale (OACI). Depuis plus de deux décennies, l'intégration au niveau international des données écologiques, mais aussi économiques, permet la mise en place de mesures de réduction du risque efficaces et proactives (Dolbeer et al., 2015). A l'inverse, la gestion des collisions entre les navires et les baleines est caractérisée par une gestion « bottom-up » qui ne prend pas – ou peu – en compte les dimensions humaines. Lorsqu'une zone à risque est identifiée, les solutions de réduction du risque sont souvent proposées sans évaluation de son impact sur le trafic maritime. Lorsqu'une solution est mise en place au niveau local, cette dernière est parfois soumise à l'Organisation Maritime Internationale (OMI) – l'équivalent de l'OACI –, sans approche systémique, ce qui entrave la prise de décision (Read, 2008; Sorby, 2018).

La question de recherche de cette thèse est donc d'identifier comment intégrer les dimensions humaines et écologiques de manière standardisée afin d'améliorer la gestion des collisions entre navires et baleines. Pour répondre à cette question, deux objectifs de recherche sont fixés : (1) définir un processus standardisé pour l'évaluation des solutions de réduction du risque ; et (2) étudier les dimensions logistiques et économiques nécessaires pour une gestion systémique de la problématique des collisions.

Pour répondre à ces objectifs, le premier chapitre de la thèse conceptualise l'utilisation d'un outil de l'OMI comme approche systémique à la proposition de solutions. Le Chapitre 2 donne un premier aperçu des dommages causés aux navires après une collision avec une baleine. Le troisième chapitre examine les préférences de l'industrie maritime pour les solutions d'atténuations du risque de collision. Le Chapitre 4 propose d'explorer la notion de sévérité de l'impact des activités humaines sur les baleines. Le dernier chapitre est une étude préliminaire pour la définition du critère de rentabilité pour les baleines, dans l'objectif d'améliorer la prise de décision des parties prenantes.

Chapitre 1 – Un cadre décisionnel pour réduire le risque de collisions entre navires et baleines

1. CONTEXTE

Comme mentionné auparavant, le manque d'approche holistique de la gestion des collisions entre navires et baleines est un frein à la mise en place de mesures efficaces. L'objectif de ce chapitre est d'étudier les possibilités pour une approche systémique analogue à celle des collisions entre les avions et la vie sauvage. En explorant les outils de l'OMI, nous avons pu trouver un outil d'analyse du risque – l'Evaluation Formelle de la Sécurité (EFS) –, pour lequel nous proposons une adaptation à la problématique des collisions avec les baleines.

L'EFS est *"un processus rationnel et systématique pour mesurer les risques liés à la sécurité maritime et à la protection du milieu marin et pour évaluer les coûts et les bénéfices des options de l'OMI pour réduire ces risques"* (IMO, 2018a). L'utilisation de l'EFS pour les questions environnementales est quelque peu limitée et s'est principalement concentrée sur les marées noires (Kontovas and Psaraftis, 2008) (Haapasaari et al., 2015; Kontovas et Psaraftis, 2008). Cependant, l'utilisation de l'EFS peut être un moyen de normaliser et de mieux évaluer le potentiel des solutions proposées pour réduire les collisions entre navires et baleines.

2. UTILISATION L'EVALUATION FORMELLE DE LA SECURITE POUR REDUIRE LE RISQUE DE COLLISION ENTRE NAVIRES ET BALEINES

L'OMI a envisagé l'EFS comme un outil d'aide à l'évaluation de nouvelles réglementations pour la sécurité maritime et la protection du milieu marin ou pour faire une comparaison entre les réglementations existantes. L'objectif de l'EFS est de parvenir à un équilibre entre les diverses questions techniques et opérationnelles, y compris la dimension humaine, la sécurité maritime, ou la protection du milieu marin ou l'économie (Kontovas et al., 2007). L'EFS est composée de 5 étapes (Fig. 1).

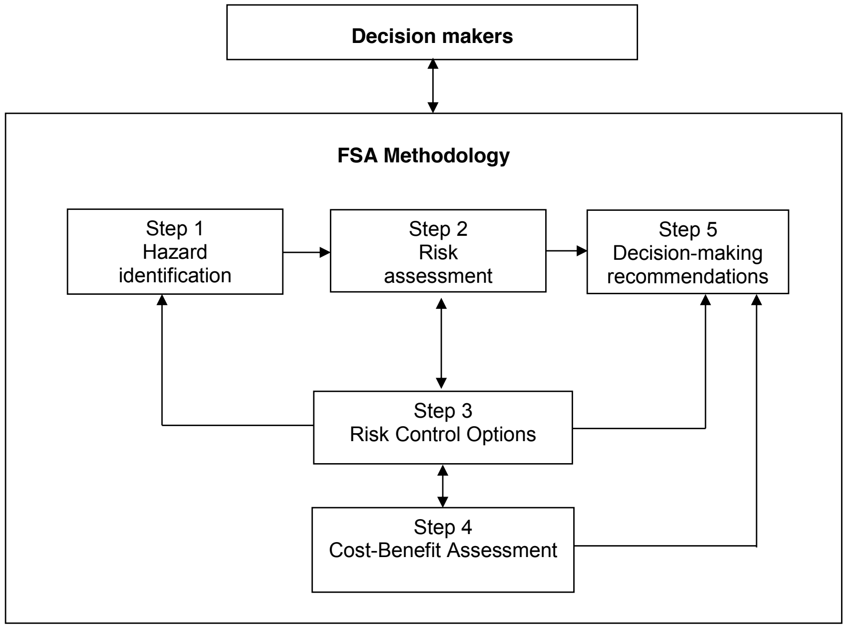

Figure 31 : Etape de l'évaluation Formelle de la Sécurité (IMO, 2018a)

Selon les directives de l'EFS (IMO, 2018a), l'étape d'identification des dangers – Etape 1 – vise à déterminer tous les scénarii potentiellement dangereux, qui pourraient entraîner des conséquences importantes en les hiérarchisant par niveau de risque. Dans notre cas d'étude, l'événement de collision est considéré comme l'événement principal. Les risques de collision ont été divisés en deux catégories principales (échec de détection et échec d'évitement) et six sous-catégories : (1) Echec de détection visuelle par l'homme ; (2) Echec de l'évitement dû à l'homme ; (3) Echec de détection par la technologie du navire ; (4) Echec de l'évitement dû à la technologie du navire ; (5) Echec de la détection et de l'évitement dû aux caractéristiques circonstancielles ; et (6) Echec de la détection et de l'évitement dû aux caractéristiques du trafic maritime. Bien que l'identification des dangers soit plutôt simple dans la littérature, leur contribution à la sévérité des collisions est difficile à estimer. En effet, les navires remarquent rarement la collision avec une baleine, et lorsqu'ils le font, elle n'est souvent pas signalée (Félix and Van Waerebeek, 2005; Jensen and Silber, 2004; Laist et al., 2001; Mayol, 2007; Monnahan et al., 2015; Priyadarshana et al., 2016; Rockwood et al., 2017).

Selon les directives de l'EFS (IMO, 2018a), l'étape d'analyse des risques – Etape 2 – vise à obtenir une mesure quantitative de la probabilité d'occurrence des contributeurs de risques et une évaluation des conséquences potentielles associées aux dangers identifiés à l'étape précédente. Au cours de ces dernières années, trois types d'analyse du risque de collisions entre navires et baleines ont émergé : (1) le calcul du nombre de mortalité en fonction des échouages –

précision basse / coût faible ; (2) le calcul d'un indicateur de collision – précision moyenne / coût moyen ; et (3) le calcul de la probabilité de collision – précision haute / coût élevé. Le défi le plus critique de l'étape d'analyse des risques est de définir le niveau de risque acceptable pour les régulateurs ou la société. La définition du risque est complexe, à cause du manque de données, et la définition de sa sévérité – risque acceptable – l'est encore plus. En effet, l'impact d'une collision doit être évalué au niveau de la population et non au niveau local (Brown et al., 2019).

Selon les directives de l'EFS (IMO, 2018a), l'Etape 3 a pour but de proposer des options de contrôle des risques (OCR) – solutions – efficaces et pratiques. Ainsi, l'une des premières tâches de l'étape 3 consiste à identifier les mesures qui réduisent le risque de collisions de baleines en fonction des principaux dangers identifiés à l'étape 1. Pour chaque OCR, l'étape 2 est répétée pour évaluer la potentielle réduction de risque induite. La réalisation de cette étape se heurte au manque d'étude *ex post* dans la littérature. En effet, la plupart des évaluations sont des analyses *ex ante* qui traitent du respect d'une solution ou de la réduction des risques induits, mais rarement des deux notions ensemble. Il y a donc un manque de données quantitatives, mais aussi qualitatives pour cette étape.

Selon les lignes directrices de l'EFS (IMO, 2018a), l'objectif de l'Etape 4 est d'identifier et de comparer les bénéfices et les coûts associés à la mise en œuvre de chaque OCR identifié et défini à l'étape 3. Les valeurs de coûts et bénéfices associés à une OCR doivent être combinées avec la réduction des risques pour évaluer les coûts et les bénéfices par pourcentage de réduction du risque (IMO, 2018a). Afin d'évaluer les mesures de réduction du risque liées aux collisions de navires avec les baleines, et en utilisant le cadre de l'EFS, il est nécessaire de définir un indice *"en termes de coût par unité de réduction des risques en divisant le coût net par la réduction des risques résultat de la mise en œuvre de l'option"*. Pour les collisions entre navires et baleines, notre étude propose donc un indice de rentabilité similaire à ce qui est fait pour les mortalités humaines (IMO, 2018a), appelé coût net pour éviter une mortalité de baleine (CNEMB), comme suit:

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

où, ΔC est le coût par navire du OCR considéré; ΔB est le bénéfice économique par navire résultant de la mise en œuvre de la OCR; ΔR est la réduction du risque, en fonction du nombre de mortalités évitées, induite par le OCR.

L'un des objectifs de l'EFS est de fournir aux décideurs (Etape 5) des recommandations de mesures qui réduisent le risque, mais qui sont aussi rentables. Pour évaluer cette rentabilité, l'indice calculé ci-dessus (CNEMB) devrait être comparé à un critère de rentabilité. Pour recommander un OCR, l'indice de rentabilité doit être inférieur au critère de rentabilité; sinon, l'OCR est rejeté par l'OMI. Les lignes directrices de l'EFS proposent trois méthodes pour définir ce critère (IMO, 2006) : (a) Observations de la volonté de payer pour éviter une mortalité; (b) Observations des décisions passées et des coûts qui en découlent; et (c) Prise en compte des indicateurs sociétaux. Ce critère est défini pour la santé et mortalité humaine, ainsi que pour les marées noires (IMO, 2000; Lind, 1996; UNDP, 1990; Kontovas and Psaraftis, 2008; Vanem, 2012). Pour les baleines, plusieurs options sont possibles et des recherches devraient être engagées pour explorer ces options. Par exemple, nous pouvons citer les axes de recherche suivants : volonté à payer pour protéger les populations de baleines (Boxall et al., 2012; Wallmo and Lew, 2012) ; les services écosystémiques (Lavery et al., 2014; Roman et al., 2014) ; ou les coûts de gestion des carcasses échouées (Couvat et al., 2016). La dernière étape – Etape 5 – de l'EFS vise à présenter des recommandations aux décideurs pour l'amélioration de la sécurité, en tenant compte des résultats des quatre étapes précédentes. Les OCRs recommandés doivent réduire le risque jusqu'au niveau désiré de protection des baleines, tout en étant efficient.

3. CONCLUSIONS ET RECHERCHES FUTURES

Le manque d'approche holistique est un frein à la mise en place de mesures d'atténuation du risque de collisions entre les navires et les baleines. Par conséquent, ce papier a proposé une approche holistique à travers un cadre d'évaluation des risques qui a été adopté par l'OMI, à savoir l'EFS. Néanmoins, plusieurs axes de recherches devraient être exploré pour améliorer ce travail. Le manque de données sur les évènements de collision entrave l'analyse du risque, mais aussi l'analyse des coûts (Etape 1, 2 et 4). Il est aussi nécessaire de normaliser les méthodes d'analyse des risques pour estimer quantitativement la fréquence et les conséquences des collisions (Etape 2). Enfin, le plus grand défi réside à l'étape 4, où le manque de données économiques et la définition du critère de rentabilité méritent un effort considérable de recherche.

Chapitre 2 – Réduire les collisions entre les baleines et les navires en évaluant mieux les dommages aux navires

1. INTRODUCTION

Les collisions entre les véhicules et la faune sauvage constituent des menaces importantes pour la conservation de la faune, mais aussi pour la sécurité humaine (Visintin et al., 2018). Des études récentes ont montré que les collisions entre les baleines et les navires se produisent plus fréquemment que prévu (Frantzis et al., 2019). De nombreuses solutions pour éviter ces collisions ont été proposées au cours des deux dernières décennies (IMO, 2009; Silber et al., 2008a). Contrairement au cas de collision entre les baleines et les navires, des approches holistiques sont mises en œuvre depuis longtemps pour d'autres types de collisions entre la faune et les véhicules (Huijser et al., 2009a). Ces approches intègrent notamment les coûts liés aux dommages sur les véhicules à la suite de collisions. Dans le cas des collisions avec les baleines, les dommages ont toujours été jugés négligeables, mais n'ont jamais été quantifiés.

L'objectif de notre étude est d'évaluer la valeur ajoutée de l'intégration des dommages des navires à la gestion des collisions entre navires et baleines. À cette fin, nous évaluons (1) la probabilité de dommages causés aux navires par une collision avec une baleine, en utilisant, entre autres, la base de données sur les collisions de la Commission Baleinière Internationale (CBI), et (2) fournissons un bref aperçu des potentiels coûts de ces dommages pour les compagnies maritimes.

2. METHODOLOGIE ET DONNEES

Pour notre analyse, nous avons recueilli des informations sur la vitesse du navire, sa longueur et les dommages associés aux événements de collision dans les banques de données de collisions de la CBI mais aussi dans des banques de données annexes et autres articles scientifiques publications (p. ex. GISIS database; Laist *et al.*, 2001; Jensen and Silber, 2004; Panigada *et al.*, 2006).

Vanderlaan and Taggart (2007) ont proposé une méthodologie pour définir la *«probabilité de blessure mortelle de baleine en fonction de la vitesse du navire»* lors de l'impact. De la même manière, nous avons calculé la probabilité de dommages au navire à la suite d'une collision avec une baleine en fonction de la vitesse ou de la longueur du navire, et de leur rapport, en effectuant une analyse de régression logistique, avec bootstrapping, à l'aide du logiciel «R» (R Development Core Team, 2008).

3. RESULTATS

Seulement 16.4% des évènements de collisions répertoriés dans nos données décrivent l'état des dommages. Les principaux dommages identifiés ont été causés aux appendices suivantes: bulbe (coque); coque; pale d'hélice; arbre de transmission; gouvernail; bras de direction; stabilisateur; T-foil. La base de données contient très peu d'informations concernant les coûts des dommages (1,2% des cas de la banque de données). A noter également, au total, 2 mortalités humaines et 194 blessures humaines sont signalés dans nos données (années 1970-2019).

Nous avons effectué trois régressions distinctes: une ne prenant en compte que la vitesse du navire, une autre avec uniquement la longueur du navire et une avec le rapport de la vitesse par la longueur – ce dernier est le modèle le plus robuste (AIC faible ; Fig. 4). La probabilité de dommages au navire après une collision avec un baleine est calculé comme suit :

$P_{damage} = \frac{1}{1+e^{-(\alpha+\beta\times\chi)}}$, avec $\alpha = -2.377,\ \beta = 3.346$, and $\chi = vitesse/longueur$

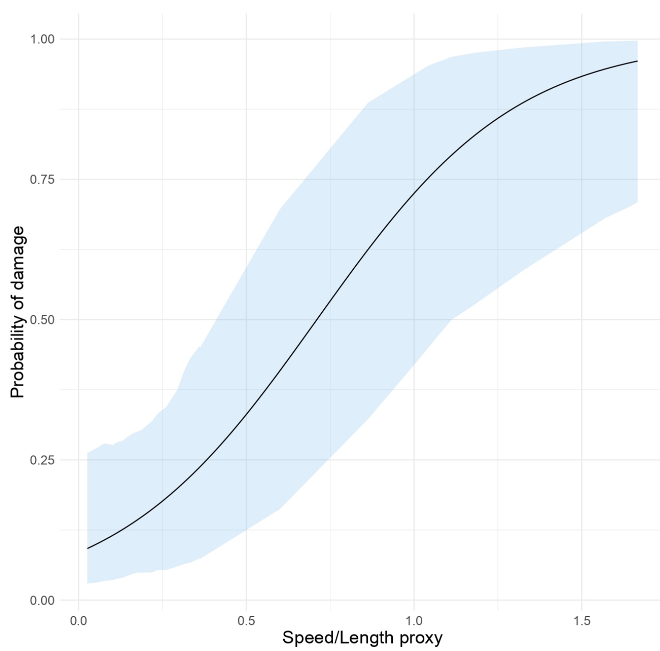

Figure 32: Probabilité de dommages au navire en fonction d'un proxy vitesse / longueur. La zone bleue représente l'intervalle de confiance.

4. DISCUSSION

La base de données sur les collisions ne contient qu'une quantité limitée de données par rapport à d'autres bases sur les collisions avec des animaux sauvages. Par exemple, l'Administration Fédérale d'Aviation américaine (FAA) a collecté 99530 collisions entre 1990 et 2014 (contre 250 pour la CBI en 40 ans; Dolbeer *et al.*, 2015). En comparant ces chiffres avec ceux des estimations de Panigada *et al.*, (2006) en Méditerranée, on constate que le nombre de collision serait du même ordre de grandeur (nombre de collision/trajet), et que la banque de données de la CBI devrait donc contenir plus d'informations.

Notre étude estime la probabilité de dommages aux navires à la suite d'une collision navire-baleine en utilisant un modèle de régression logistique conforme à Vanderlaan and Taggart (2007). Ce modèle souffre donc des mêmes limites (p. ex. taille des baleines, résistance de la coque).

De manière globale, un navire a une chance sur dix d'être endommagé après une collision avec une baleine. Les résultats montrent que les navires Cargo-Ferries sont les plus exposés aux dommages, en particulier les ferries à passagers et les navires à passagers à grande vitesse. Notez que cette étude évalue la probabilité de dommages mais ne traite pas de la gravité des dommages, car il n'y a pas suffisamment de données dans la base de données CBI.

Les coûts associés aux dommages des navires peuvent être divisés en deux catégories : coût de réparation et coûts associés à la perte d'activité (IMO, 2010 ; Stopford, 2009). Nous estimons que les coûts de réparation peuvent atteindre plusieurs centaines de milliers de dollars, et que les pertes de revenus sont potentiellement supérieures à ces coûts.

L'évaluation des dommages et des coûts est cruciale pour gérer plus efficacement les collisions entre les baleines et les navires. Des leçons peuvent être tirées de la gestion des autres cas de collisions entre les véhicules et la faune. Bien qu'ils soient jugés faibles par l'industrie des transports, les dommages et leurs coûts associés sont souvent pris en compte pour équilibrer les bénéfices et les coûts (ICAO, 2009). L'évaluation des dommages permet à la fois de réduire les coûts des solutions d'atténuation, mais aussi de réduire les risques environnementaux et humains associés aux collisions (Bissonette et al., 2008; Huijser et al., 2009a; Visintin et al., 2018).

Chapitre 3 – Évaluation des préférences de l'industrie du transport maritime pour les solutions de réduction des risques de collision entre navires et baleines

1. INTRODUCTION

Le trafic maritime menace la biodiversité à bien des égards. La pollution chimique ou sonore peut être décrite comme les principaux impacts indirects de la navigation sur les espèces marines. De plus, les navires sont responsables de l'élimination directe – mortalité – de la mégafaune marine, tels que les baleines ou les tortues marines, lors des collisions avec les navires (Panigada et al., 2008; Pirotta et al., 2018). Pour les baleines, les collisions avec des navires sont l'une des principales menaces à la survie de certaines populations (IWC-ACCOBAMS, 2012; Reimer et al., 2016). Malgré la proposition de différentes solutions d'atténuation, l'efficacité de celle-ci est limitée à cause du faible respect des compagnies maritimes envers ces solutions (Sèbe et al., 2019). Les facteurs amenant ce faible respect sont divers, mais le manque d'intégration des dimensions logistiques et économiques du transport maritime lors des propositions de solutions semblent être un frein à la volonté d'agir des compagnies (Notarbartolo di Sciara, 2016; Sèbe et al., 2019, 2020). Peu de recherches se sont portées sur les dimensions économiques (p. ex. Gonyo et al., 2019), et encore moins sur les dimensions logistiques (p. ex. Reimer et al., 2016).

Notre étude cherche à comprendre les préférences des compagnies maritimes pour deux solutions de réduction du risque : évitement et réduction de vitesse.

2. MÉTHODES

Les méthodes du « choice experiment » (CE) sont souvent utilisées pour évaluer les préférences des différentes parties prenantes concernant les politiques environnementales (Garrod et al., 2012). La préférence entre les attributs est généralement révélée par une valeur de consentement à payer, qui peut être utilisée comme valeur monétaire ou comme indicateur du changement d'utilité (Garrod et al., 2012; Morey et al., 2008). En utilisant la méthode CE, nous proposons à l'industrie du transport maritime deux solutions d'atténuation, chacune étant un attribut des alternatives : l'évitement (AS) et la réduction de vitesse (SRS) dans la zone à forte probabilité de collision. Pour que l'industrie du transport maritime choisisse l'une de ces solutions, les alternatives sont également composées d'autres attributs représentant des caractéristiques situationnelles (Fig. 3) : la taille - le diamètre - de la zone à haute densité de baleines (AOI) ; l'heure de réception des informations (TRI) sur les caractéristiques de l'AOI ; et la distance de déplacement (TD).

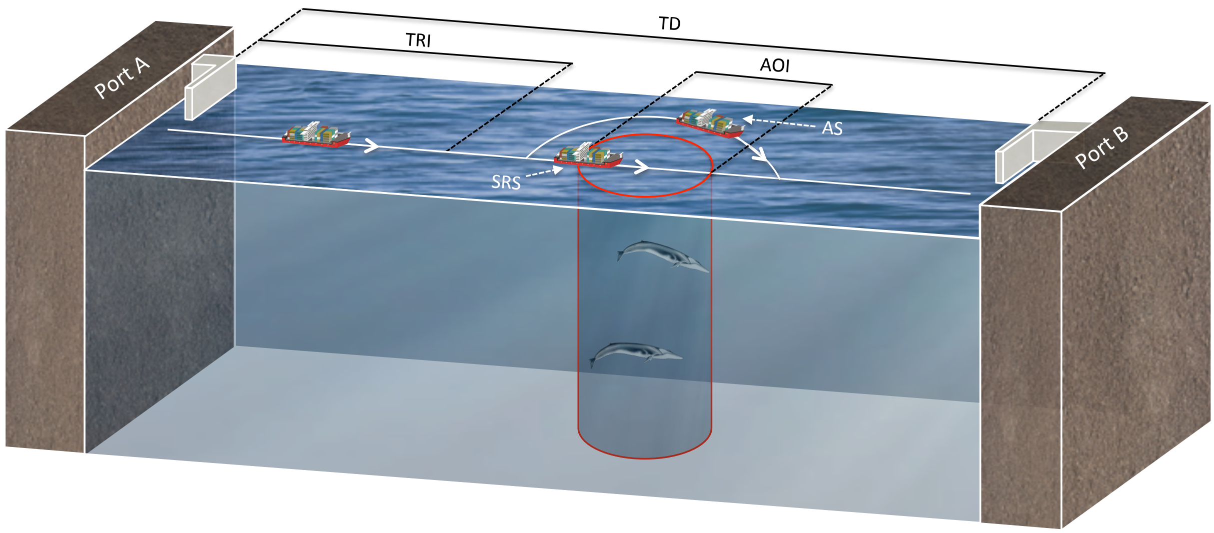

Figure 33: Illustration conceptuelle du questionnaire. Notez que l'AS peut être combiné avec le SRS dans le questionnaire. TD = Travel distance; TRI = Time of information reception; AOI = Size of the area of interest; AS = Avoidance solution; SRS = Speed reduction solution

Pour chaque ensemble de choix, on a demandé aux répondants de supposer qu'ils avaient effectué les deux alternatives. Sur la base de ce principe, les répondants doivent répondre à la question suivante: *"A votre avis, quelle alternative représente le meilleur compromis entre les enjeux du trafic maritime et la protection des baleines?"*. Trois réponses étaient possibles *"Alternative 1"*, *"Alternative 2"* et *"Aucune des alternatives n'est réaliste"*. Le traitement des réponses aboutit à la création de modèles « mixed logit » fondé sur une fonction d'utilité aléatoire non-linéaire.

3) RESULTATS

Au total, 67 répondants ont rempli le questionnaire, ce qui représente 19,7% de la taille de l'échantillon. La plupart des répondants embarquaient sur des cargos de tailles allant de 100 m à 250 m. Parmi les modèles testés, le modèle *« mixed logit »* apparaît comme le plus robuste (BIC le plus faible). En ce qui concerne les attributs des caractéristiques situationnelles, les résultats montrent que la préférence de l'équipage augmente positivement avec l'attribut de distance de déplacement (TD; Fig.3). De même, les préférences pour l'heure de réception des informations (TRI) sont positives jusqu'à un point d'inflexion à 15h19 ; à partir de ce point, il n'y a pas de valeur ajoutée à avoir plus de temps pour préparer le voyage. Sans surprise, l'équipage préfère les zones d'intérêt limitées en taille.

4. DISCUSSIONS ET CONCLUSIONS

Dans cette recherche, nous avons étudié les préférences de l'industrie du transport maritime pour les solutions d'atténuation. L'évitement semble être la solution la plus appréciée des équipages de navires. Sur le plan économique, cette préférence semble logique ; en comparaison avec la réduction de vitesse, l'évitement permet plus facilement de compenser les coûts engendrés (Gonyo et al., 2019). Nos résultats soulignent l'importance de recevoir des informations en amont sur les caractéristiques du domaine d'intérêt, en particulier pour les officiers de quart.

Les scientifiques de la conservation proposent souvent la solution théoriquement la plus efficace lorsqu'une menace de collision est identifiée. Mais bien que théoriquement efficace, l'efficacité appliquée de la solution de réduction de vitesse est souvent limitée. Les préférences de l'industrie du transport maritime exprimées dans notre étude préconisent l'utilisation de solutions d'évitement au lieu de celles de réduction de vitesse. Les principales préférences de l'industrie du transport maritime et des scientifiques de la conservation sont donc dichotomiques. En conséquences, pour parvenir à une protection plus efficace des baleines, les scientifiques de la conservation devraient intégrer les préférences de l'industrie du transport maritime avant de présenter une solution d'atténuation.

Pour pouvoir compenser les coûts des solutions d'atténuation, les navires doivent être informés à l'avance des caractéristiques de la zone d'intérêt. L'évolution des modèles actuels d'habitat de baleines vers des modèles plus dynamiques est donc nécessaire pour obtenir ce type de notification.

Nos résultats peuvent être utilisés comme lignes directrices pour la propositions de solutions. Cela peut être notamment utile au niveau de l'OMI afin de proposer des solutions viables au niveau des sites d'étude, et ainsi d'améliorer la transparence des propositions.

Chapitre 4 – Mortalité directe de baleines induite par l'homme dans les sous-populations méditerranéennes : mortalité excessive ?

1. INTRODUCTION

Les sous-populations méditerranéennes de rorquals communs (*Balaenoptera physalus*) et de cachalots (*Physeter macrocephalus*) sont grandement menacées, notamment par les interactions directes avec l'homme, telles que les collisions avec les navires et les enchevêtrements (Notarbartolo-Di-Sciara, 2014; Ritter and Panigada, 2019). Si le nombre de mortalités induites par ces menaces directes (Human-Induced Direct Mortality ; HIDM) a pu être estimé au niveau local, dans des zones à risques (p. ex. Panigada et al., 2006), ce nombre est rarement mis en perspective à l'échelle de la population Méditerranéenne. En effet, que ce soit dans cette mer, ou dans d'autres océans, les conséquences sur les populations d'un nombre de mortalités identifiées au niveau local sont rarement évaluées (Brown et al., 2019). Par conséquent, la prise de décision des structures réglementaires est souvent entravée par le manque de transparence sur les sévérités de ces activités humaines (Carwardine et al., 2008; IMO, 2018a; Vanem, 2012).

Ce manque d'évaluation des conséquences est principalement dû au manque de données. En revanche, la caractéristique semi-fermée du bassin Méditerranéen empêche une perte de données d'échouages que l'on peut observer dans les bassins ouverts. Ainsi, l'objectif de ce papier est d'utiliser cette caractéristique afin de définir le nombre de mortalités induites par ces menaces directes – par la méthode du taux de récupération des carcasses –, et d'en évaluer la sévérité grâce à des règles de gestion (Points de Référence Limites; PRL ; Curtis et al., 2015).

2. MATERIELS ET METHODES

Nous avons estimé le nombre de HIDM pour les rorquals communs et les cachalots en utilisant l'approche de récupération des carcasses, de la même manière que les études de Heyning and Dahlheim (1990), Kraus (2005), and Williams et al. (2011). En utilisant les données d'échouages, nous avons définis le nombre moyen d'échouages dû à des causes naturelles. Nous avons ensuite estimé le taux de récupération des carcasses en divisant ce nombre par le nombre théorique de mortalité naturelle à l'échelle de la population (Taylor et al., 2007; Williams et al., 2011). En appliquant ce même taux aux nombres de mortalités dues aux collisions et enchevêtrements rencencés dans les échouages, nous obtenons le nombre de mortalités dues à ces menaces à l'échelle de la population Méditerranéenne. Ensuite, nous faisons le ratio de cette mortalité par rapport à deux règles de gestion pour définir la sévérité de cette mortalité (Potential Biological Removal (PBR) and Critical Reference Point (CRP); Caswell et al., 1998; Wade, 1998).

3. RESULTATS

Notre analyse des bases de données suggère qu'une moyenne de 7,1 rorquals communs et 9,3 cachalots échouent sur les côtes méditerranéennes chaque année (données de 2005 à 2015). Le nombre de HIDM varie en fonction de l'abondance et du nombre de mortalité naturelle identifiées dans les échouages (Fig. 2).

En prenant le nombre moyen de mortalité naturelle dans les échouages (ligne noire sur la Figure 2), le nombre de mortalités directes de rorquals communs dues à l'homme en Méditerranée est 8,2x supérieur au PBR et 0,8x inférieur au CRP, indépendamment de l'abondance. Pour le cachalot, le nombre de mortalités directes dues à l'homme est 4,8x supérieur au PBR et 0,5x inférieur au CRP, indépendamment de l'abondance.

4. DISCUSSION

Nos résultats confirment que le statut UICN de la sous-population de rorquals communs méditerranéens doit être réévalué, comme indiqué dans la littérature la plus récente (Notarbartolo di Sciara et al., 2016). Nos résultats démontrent un impact moindre de la mortalité directe induite par l'homme sur la sous-population méditerranéenne de cachalots que sur celle des rorquals communs. Cependant, la mortalité indirecte induite par l'homme semble représenter une menace à la survie des cachalots de Méditerranée (p. ex. pollution, études sismiques, épuisement des proies).

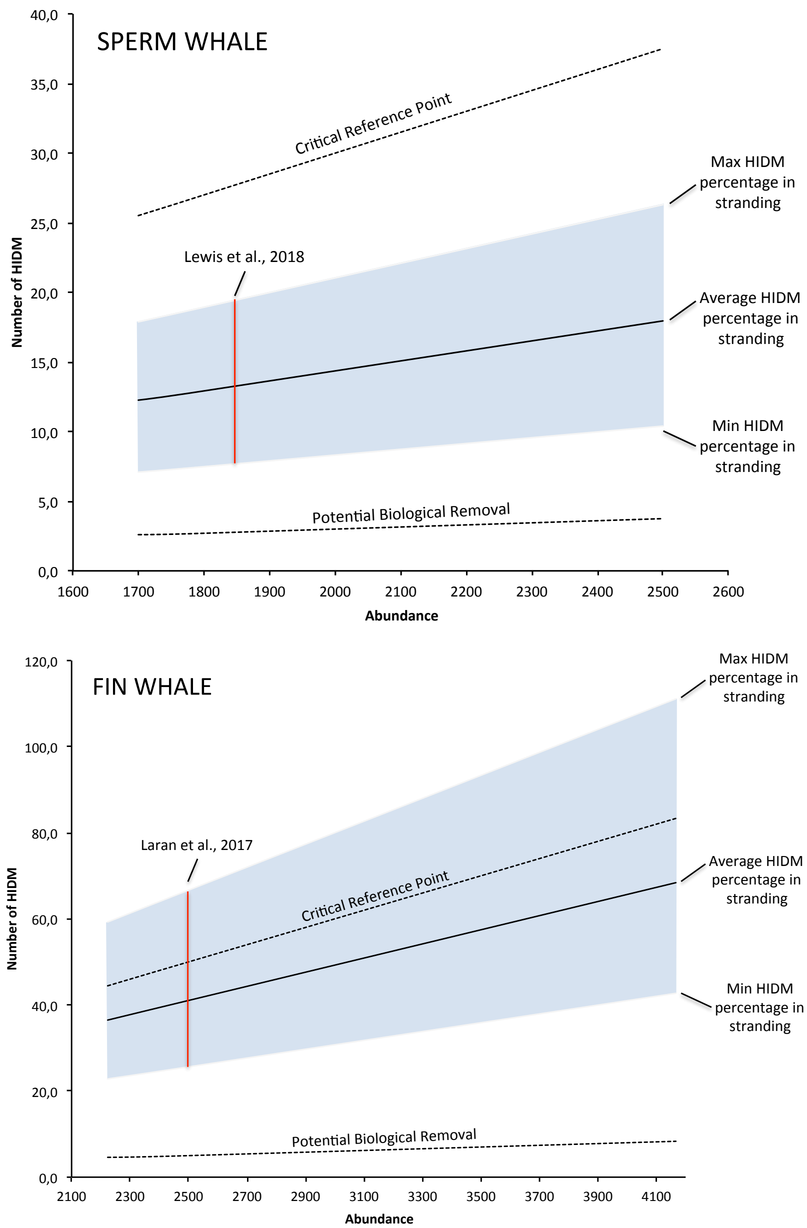

Figure 34: Nombre de mortalité directe en fonction de l'abondance et de la proportion de mortalité naturelle dans les échouages. La ligne noire représente le nombre de mortalité directe correspondant au pourcentage moyen de mortalité naturelle dans les échouages en Méditerranée. La zone en bleu représente l'éventail des possibilités de pourcentages de mortalité naturelle dans les échouages sur la base des valeurs minimales et maximales dans les bases de données des réseaux d'échouage. Les lignes pointillées correspondent au PBR et au CRP. Les lignes rouges correspondent aux valeurs d'abondance utilisées comme illustrations dans cette étude.

Une analyse transparente du risque est une valeur ajoutée au processus de décision pour la mise en œuvre des mesures d'atténuation du risque (Carwardine et al., 2008; Claudet and Fraschetti, 2010; IMO, 2018a; Vanem, 2012). La gravité du risque HIDM sur les baleines méditerranéennes suggère des recommandations de conservation légèrement différentes pour chaque espèce. À l'échelle locale, les efforts devraient se poursuivre pour atténuer l'impact des collisions et des enchevêtrements dans les points chauds identifiés. À l'échelle régionale et internationale, l'ACCOBAMS devrait réviser ses recommandations concernant les règles de gestion, en particulier pour les rorquals communs. Dans leurs directives, l'ACCOBAMS préconise des prélèvements inférieurs à 2% de la sous-population (ACCOBAMS, 2016) – ce qui représente en réalité la moitié du taux de survie dans le calcul d'origine (IWC, 1996, 1991). Nous préconisons pour la mise en œuvre d'une règle de gestion plus stricte à 1% de la population - un quart du taux de survie -, comme cela a été fait pour certaines populations par l'ASCOBANS (Caswell et al., 1998; Reeves and Brownell, 2009).

Un cadre plus réglementaire devrait être mis en œuvre pour gérer la mortalité induite par l'homme, au moins pour les mortalités directes (Geijer and Jones, 2015; Sèbe et al., 2019; G. K. Silber et al., 2012). Par exemple, pour les collisions, il existe plusieurs façons de mettre en œuvre des mesures obligatoires au niveau de l'OMI, telles que: (1) proposer des solutions d'atténuation au Comité de la Protection du Milieu Marin (MEPC; par exemple, IMO, 2007); (2) proposer une Zone Maritime Particulièrement Vulnérable (PSSA; IMO, 2016, 2006)- dans laquelle la mise en œuvre de mesures de réduction des risques est possible; (3) une possible implication dans la désignation potentielle de la zone méditerranéenne de contrôle des émissions (ECA) (Redfern et al., 2019) - pour guider la réduction de la vitesse dans les points chauds des collisions; et (4) proposer des solutions à travers le cadre d'évaluation des risques de l'OMI, à savoir l'Evaluation Formelle de la Sécurité (EFS; Sèbe et al., 2019).

Pour les cas méditerranéens, l'approche de récupération des carcasses permet d'évaluer la gravité de l'impact malgré le manque de données concernant les paramètres de population. Cependant, afin d'affiner les résultats de cette approche, une amélioration de l'identification des causes de mortalité dans les échouages et sur les paramètres de survie est réellement nécessaire (Arregui et al., 2019; Peltier et al., 2016; Peltier and Ridoux, 2015).

Chapitre 5 – Critère d'évaluation des risques: Evaluation des mesures de réduction des collisions – Une étude de cas méditerranéenne

AVANT-PROPOS

Ce chapitre est exploratoire et donne un premier aperçu de la définition d'un critère d'évaluation du risque pour les baleines. Ce travail pourrait être poursuivi après cette thèse afin de surmonter les limites identifiées.

1. INTRODUCTION

Les collisions entre navires et baleines constituent une menace majeure pour la survie de certaines populations (Ritter et Panigada, 2019). Plusieurs solutions ont été proposées pour atténuer l'impact des collisions. Cependant, la conformité de l'industrie du transport maritime à ces solutions est souvent limitée (Chion et al., 2018; Freedman et al., 2017). Récemment, l'application d'un cadre d'évaluation des risques mis en place par l'Organisation Maritime Internationale (OMI), à savoir l'évaluation formelle de la sécurité (EFS), a été conceptualisée pour le cas des collisions de navires-baleines afin de surmonter ce manque de mise en conformité (Sèbe et al. , 2019). L'EFS suit le raisonnement des techniques d'évaluation des risques et recommande une approche en cinq étapes (voir Chapitre 1). Lors de l'étape d'analyse des coûts et bénéfices (Etape 4), les lignes directrices de l'EFS n'intègrent que les coûts et bénéfices privés. Cependant, dans ces mêmes lignes directrices, la définition de critères d'évaluation des risques est proposée afin d'intégrer les bénéfices sociétaux. Des critères d'évaluation des risques ont été définis pour la santé humaine et les marées noires (OMI, 2004; Kontovas et al., 2010; Vanem, 2012).

Dans la même logique, ce chapitre exploratoire vise à définir un tel critère d'évaluation – coût de la prévention d'une mortalité de baleine – pour les solutions d'atténuation des risques en utilisant le consentement à payer (CAP) du public pour la préservation des baleines. La section 2 de ce chapitre définit le cadre de calcul de ce critère basé sur la valeur d'une population de baleines, ainsi que l'application de cette approche au rorqual commun de la Méditerranée – notre étude de cas. La section 3 traite de l'utilisation de ce critère dans le contexte de l'EFS. Enfin, la dernière section conclut sur les limites de cette approche et les recherches supplémentaires requises sur le sujet.

2. ÉVALUER LES BENEFICES DE RÉDUIRE LE RISQUE DE COLLISION ENTRE BATEAUX ET BALEINES

2.1. CALCUL DU CRITERE D'EVALUATION DES RISQUES

Nous extrapolons la valeur d'une population de baleine en fonction du CAP pour sa conservation, du nombre d'habitant à proximité de la zone d'étude, pondéré par la distance de ces habitants par rapport à la zone d'étude (Loomis, 2000). Bien que le calcul de la valeur d'une population de baleine en utilisant la relation entre le CAP et la distance de la zone d'étude (Loomis, 2000) soit directe, la définition de cette valeur en fonction de l'abondance est plus complexe, mais nécessaire pour évaluer les changements de cette valeur en fonction de la mortalité des baleines. Par conséquent, nous utilisons les comportements du CAP observés dans la littérature pour construire une fonction linéaire entre la valeur d'une population et l'abondance.

L'objectif principal de ce travail est d'examiner les bénéfices sociétaux d'une baleine - alias le coût de la prévention de la mortalité d'une baleine. Pour définir le coût de la prévention d'une mortalité de baleine - critère d'évaluation des risques -, nous estimons, grâce à la fonction linéaire, la différence de valeur théorique entre une population où une règle de gestion est respectée et une population où cette règle de gestion n'est pas respectée. Pour ce faire, nous utilisons le Potential Biological Removal (PBR) comme règle de gestion.

2.2. APPLIQUATION AU CAS DES RORQUALS COMMUNS DE MEDITERRANEE

A la connaissance des auteurs, aucune étude n'a défini le CAP pour conserver la sous-population de rorquals communs méditerranéens. Nous avons donc construit une fonction de transfert de bénéfices en fonction des banques de données de Amuakwa-Mensah (2018) et du

USGS Benefit Transfer Toolkit. Nous avons utilisé cette fonction pour calculer la valeur de la population V_{pop_t} et le critère d'évaluation du risque φ_{2017}.

$$V_{pop_{2017}} = \$25{,}532{,}058{,}838 \text{ (US\$2017)}$$

$$\varphi_{2017} = \$562{,}462 \text{ (US\$2017)}$$

3. UTILISATIONS POTENTIELLES DANS L'ÉVALUATION DES RISQUES MARITIMES

Comme mentionné précédemment, l'EFS est *« un processus rationnel et systématique pour mesurer aux risques liés à la sécurité maritime et à la protection du milieu marin et pour évaluer les coûts et les bénéfices des options de l'OMI pour réduire ces risques »* (OMI, 2018). Dans le cadre de la sécurité humaine, pour aider les décideurs à choisir entre plusieurs solutions, leurs ratios sont comparés au *«rapport coût-efficacité différentiel maximal acceptable»* λ pour la sécurité humaine (Culyer, 2010), alias le coût de la prévention d'une mortalité. Une solution de réduction des risques devrait être recommandée pour adoption si la valeur de son rapport coût-efficacité est inférieure à λ; sinon, cette solution ne devrait pas être recommandée.

Pour les baleines, Sèbe et al., (2019) ont plaidé pour la définition du coût de la prévention d'une mortalité de baleine. Ce chapitre propose une valeur de ce coût à travers le critère d'évaluation des risques ($\lambda = \varphi_{2017} = \$562{,}462$). En Méditerranée, la seule solution économiquement évaluée est le système de traçage en temps réel des cétacés (REPCET). La comparaison du rapport coût-efficacité de REPCET au critère défini dans ce chapitre montre que l'OMI recommanderait cette solution - si le critère devait être accepté dans les lignes directrices de l'EFS (IMO, 2018).

4. CONCLUSIONS ET FUTURE RECHERCHE

Dans notre étude, nous avons utilisé la valeur d'existence pour estimer un critère d'évaluation des risques du rorqual commun méditerranéen. L'établissement d'un critère d'évaluation des risques adéquat pourrait augmenter le nombre de mesures en faveur des baleines approuvées au niveau de l'OMI, car cela augmenterait la transparence des propositions. Cependant, notre approche comporte des limites

L'utilisation de la valeur d'existence pour attribuer une valeur monétaire aux baleines a souvent été critiqué dans la littérature (Babcock, 2013). D'autres approches sont, de nos jours, recommandées pour empêcher l'utilisation de valeurs monétaires pour les êtres vivants (p.ex. services écosystémiques. Cependant, lorsqu'on étudie la mégafaune charismatique en danger de disparition - comme les populations de baleines -, les services écosystémiques présentent également des limites. En effet, la mort d'une baleine pourrait ne pas entraîner de changements significatifs dans la contribution à l'écosystème, mais pourrait être significatif pour la survie de la population de baleine (Admiraal et al., 2013; Freeman et al., 2014). Par conséquent, il existe une dichotomie entre l'importance unitaire d'une baleine dans l'écosystème et son importance intrinsèque pour la population. Ceci étant dit, les recherches sur les services écosystémiques des baleines ne sont qu'à leurs prémices (Cook et al., 2020), et de nouvelles avancées pourraient surmonter cette limite.

Outre les problèmes éthiques et le manque d'alternatives viables à l'utilisation de la valeur d'existence, notre approche se heurte à d'autres limites techniques de cette méthode d'évaluation. Entre autres, notre étude a évalué la valeur d'existence de la population de rorquals communs méditerranéens, sans tenir compte des cachalots (*Physeter macrocephalus*), une autre population à risque en Méditerranée (Frantzis et al., 2015; Rendell et Frantzis, 2016). Ce manque d'intégration pourrait faire varier le coût de la prévention d'une mortalité de baleine.

Par ailleurs, les hypothèses sélectionnées pour construire le critère d'évaluation des risques peuvent être discutables, et le critère peut donc être amélioré, comme cela a été fait par le passé pour celui des marées noires. Par exemple à l'instar de Bulte et Van Kooten (1999), nous supposons une relation linéaire entre l'abondance et le CAP, ce qui n'est pas tout à fait exact dans la réalité, et qui conduit à un critère fixe. Or, les critères fixes ont été critiqués par le passé, et les études tendent vers des critères variables. Ainsi, de nouvelles recherches sont nécessaires pour tendre vers ce type de critère.

Discussion générale

1. PRINCIPALES CONCLUSIONS DE LA THÈSE

Dans le Chapitre 1, nous avons conceptualisé l'utilisation de l'évaluation des risques de l'Organisation Maritime Internationale (OMI), à savoir l'Evaluation Formelle de la Sécurité (EFS), pour intégrer les dimensions humaines et écologiques à la question des collisions entre les baleines et les navires dans un cadre normalisé. Ce procédé permettrait de proposer de manière plus transparente des solutions d'atténuation du risque aux décideurs, et donc d'augmenter l'efficacité appliquée de ces solutions.

Le Chapitre 2 a exploré les dommages potentiels des navires à la suite d'une collision entre une baleine et un navire. En suivant la méthodologie de Vanderlaan and Taggart (2007), nous avons estimé la probabilité – moyenne – de dommages au navire après une collision avec une baleine à 0.1. Les coûts de réparation dus aux collisions peuvent atteindre plusieurs centaines de milliers de dollars. Les pertes de revenus, liées à l'inactivité des navires pendant la phase de réparation, sont probablement plus élevées que les coûts de réparation. A l'instar de l'OACI pour les collisions entre avions et oiseaux, ces dommages évités devraient être intégrés à l'analyse des solutions d'atténuation des collisions.

Dans le chapitre 3, nous avons abordé les caractéristiques logistiques qui entravent la conformité de l'industrie du transport maritime avec les solutions d'atténuation des collisions. Nos résultats montrent une préférence pour la solution d'évitement par rapport à la réduction de vitesse. Une amélioration des connaissances sur les habitats apparaît essentielle pour communiquer en amont aux navires les informations nécessaires à la prise de décision. Nos résultats peuvent être utilisés comme lignes directrices pour la sélection de solutions d'atténuation.

Le Chapitre 4 a examiné l'évaluation de la sévérité du risque de mortalité directe des baleines de Méditerranée. Les résultats mettent en évidence un niveau de risque qui n'est pas en adéquation avec la survie de ces populations. Une amélioration de l'indentification des causes de mortalité dans les échouages permettrait une distinction entre la mortalité due aux collisions et aux enchevêtrements. A terme, cela permettrait d'évaluer quantitativement l'impact des collisions sur les populations méditerranéennes.

Dans le Chapitre 5, le processus décisionnel de l'EFS a été étudié à travers une première définition du critère de rentabilité pour les baleines. Ce critère aide à définir si les coûts engendrés par une solution sont trop élevés pour le trafic maritime. Nos résultats montrent un critère de rentabilité de 562 462 $ pour le rorqual commun de méditerranée. A noter, que ce Chapitre est un travail préliminaire qu'il convient d'améliorer dans le futur.

2. IMPLICATION POUR LA CONSERVATION

2.1. L'IMPORTANCE DE L'OMI POUR LA GESTION DES COLLISIONS ENTRE NAVIRES ET BALEINES

Alors que des solutions d'atténuation des collisions avec les baleiniers ont été mises en œuvre depuis deux décennies, une récente poussée vers une gestion réglementaire internationale des collisions a été constatée dans la littérature (Geijer et Jones, 2015; Sèbe et al., 2019; Silber et al., 2012). L'OMI présente des caractéristiques clés pour la gestion des collisions entre les baleines et les navires: (1) étant une *«autorité de longue date dans le transport maritime international»* (Geijer et Jones, 2015); (2) traitant de *«tous les aspects de la sécurité maritime et de la protection du milieu marin»* (Kontovas et Psaraftis, 2009); (3) produisant *«des conventions qui deviennent lois lorsqu'elles sont promulguées par chaque État maritime»* (Stopford, 2009); (4) proposant un *«mécanisme de mise en œuvre de solutions d'atténuation quelle que soit l'échelle»* (Geijer et Jones, 2015); (5) représentant *«plus de 170 États membres»* (Geijer et Jones, 2015). En d'autres termes, l'OMI offre un cadre juridique pour la gestion des collisions similaire à celui des autres cas de collisions entre véhicules et faunes, en particulier celui de l'aviation.

2.2. L'IMPORTANCE DE L'ÉVALUATION ÉCONOMIQUE ET LOGISTIQUE

Cette thèse a mis en évidence le manque de connaissances concernant l'impact économique des solutions d'atténuation des collisions baleines-navires. A travers les différents chapitres de cette thèse, nous avons tenté de mettre en évidence les enjeux de l'intégration des dimensions économiques - et logistiques. Selon nos principaux résultats, les coûts des solutions se situent dans la fourchette des dépenses acceptables pour l'industrie maritime, mais étant donné qu'ils ne sont que rarement évalués, l'industrie maritime n'adopte que très rarement ces solutions par manque de transparence.

3. LIMITES ET PERSPECTIVES

3.1. LIMITES

Bien que l'approche systémique de la gestion des collisions entre navires et baleines soit prometteuse, sa mise en œuvre au niveau de l'OMI reste difficile. La dimension temporelle entre la conservation et l'industrie du transport maritime peut être un frein à la mise en œuvre de solutions de collision baleine-navire. En effet, le processus décisionnel de l'OMI, peut être long, compte tenu du nombre d'États membres et des enjeux (Hosli et Dörfler, 2019; Psaraftis, 2019), ce qui est en opposition avec l'urgence de la menace qui plane sur certaines populations de baleines (Cates et al., 2016; IWC, 1999a; Ritter and Panigada, 2019). Par ailleurs, le retard de la politique de conservation de l'environnement dans le domaine marin pourrait être un frein à la mise en œuvre d'approches holistiques (Jaarsma, 1997; Kociolek et al., 2015).

3.2. PERSPECTIVES

La définition du risque acceptable diffère entre les scientifiques de la conservation et l'industrie du transport maritime. Ces traitements asynchrones du risque acceptable sont des limites à la compréhension mutuelle entre les scientifiques de la conservation et l'industrie du transport maritime. Par conséquent, des recherches supplémentaires sont nécessaires pour aligner le traitement du risque acceptable de l'industrie et de la conservation. Les scientifiques de la conservation devraient aussi intégrer la notion d'efficacité théorique, d'efficience et d'efficacité appliquée afin d'améliorer la sélection de solutions de protection des mammifères marins.

Si l'EFS fournit un cadre pour une approche systémique, nous plaidons pour le développement d'approches similaires au-delà de la portée de l'EFS. Par exemple, les propositions au Comité de Protection du Milieu Marin (MEPC) de l'OMI ou les propositions des Zones Maritimes Particulièrement Vulnérables (ZMPV) peuvent s'appuyer sur l'approche de l'EFS en intégrant les aspects logistiques et économiques, ce qui fait cruellement défaut dans les propositions actuelles concernant les baleines. Cela permettrait de surmonter certaines limitations de l'EFS et des propositions actuelles, et fournira à l'OMI les informations requises pour la prise de décision.

GLOSSARY

Table Glossary: Subject index with acronyms, definitions, references and main mentions in the Manuscript. Abbreviations: **I** = Introduction; **C1** = Chapter 1; **C2** = Chapter 2; **C3** = Chapter 3; **C4** = Chapter 4; **C5** = Chapter 5; **D** = General Discussion. The numbers following the abbreviations correspond to the sections or sub-sections of the related part of the Manuscript.

Subject	Acronym	Definition	Reference(s)	Main mentions in the Manuscript
Acceptable risk	-	Level of risk, which requires no further reduction. This level corresponds to the level of loss – human, property, or environmental – that can be tolerated by an individual, household, group, organization, community, region, state, or nation.	Düzgün and Lacasse, 2005; Svalova, 2018	**C1**-2.3.; **C4**-4.3.; **D**-1., -3.2.1.
Agoa Sanctuary	-	Specially protected area under the Cartagena Convention that aims to ensure good marine mammal conservation by protecting both the mammals and their habitats from the direct or indirect, potential or proven, adverse impacts of human activities.	Agoa Sanctuary website	**I**-2.2.1.; **D**-2.1.
Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area	ACCOBAMS	Intergovernmental agreement aiming at *"achieving and maintaining a favorable conservation status for cetaceans"*.	ACCOBAMS, 1996	**I**-2.2.1.; **C1**-1.; **C4**-1., -2., -4.2., -4.3.
Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas	ASCOBANS	Intergovernmental agreement aiming at *"achieving and maintaining a favorable conservation status for cetaceans"*.	Reijinders, 2015	**C4**-4.3.
As Low As Reasonably Practicable	ALARP	Principle or criterion recognizes that a vision-zero strategy to reduce all risks as much as possible, irrespective of the associated costs, is not feasible and that a balance must be sought between the costs of risk mitigation strategies and the benefits of these safety investments.	Coile et al., 2019	**C1**-2.3.; **D**-3.2.1.
Automatic Identification System	AIS	Automatic Identification System (AIS) is a short-range coastal tracking system used on ships and by Vessel Traffic Services (VTS) for identifying and locating vessels by electronically exchanging data with other nearby ships and VTS stations. Information such as unique identification, position, course, and speed can be displayed on a screen or an ECDIS.	Euro Maritime	**I**-3.1.; **C2**-2.2., -4.1.; **C3**-4.2.
Benefit transfer	-	Refers to the use of estimated non-market values of environmental quality changes from one study in the evaluation of a different policy that is of interest to the analyst.	U.S. EPA, 2014	**C5**-2.1., -2.3.1., -2.3.2., -2.4.
Bulk carrier	-	Merchant ships specially designed to transport unpackaged bulk cargo, such as grains, coal, ore and cement. Bulk Carriers range in size from single-hold bulkers with a capacity of about 10,000 tdw to vessels, which are able to carry 365,000 metric tons deadweight.	Euro Maritime	**I**-1.2.2.; **C2**-2.3., -3.2.; **C3**-2.2.
Bycatch	-	Portion of a commercial fishing catch that consists of marine animals caught unintentionally.	Merriam-Webster Dictionary	**I**-1.2.2.
Cargo	-	Non-human transportation of merchandise that is not carried by bulk carriers or tankers (e.g., cars, containers).	In this thesis	**I**-1.2.2.; **C2**-2.3., -3.2.; **C3**-2.2., -4.3.
Cetacean	-	Aquatic mammal infraorder which includes, among others: whales, dolphins, and porpoises.	Shirihai and Jarrett, 2007	**I**-1.; **C1**-1.

Competitive exclusion	-	Doctrine that the proliferation of one species occurs at the expense of other species.	Pianka, 1974 in Czech, 2000	**I**-1.2.; **D**-3.1.1.
Compliance	-	Process of conforming, submitting, or adapting as required or requested.	Merriam-Webster Dictionary	**I**-3.1.; **C1**-1., -2.4.; **C2**-1.; **C3**-1., -4.1., -4.2., -4.4.; **C4**-4.3; **C5**-1., -3.2., -4.; **D**-1., -2.1.,- 2.2., -3.2.1., -3.2.2.
Consequence	-	Outcome of an accident.	IMO, 2018	**I**-2.1.2; **C1**-2.3; **C4**-2.; **C5**-3. **D**-1., -3.2.1.
Conservationist	-	Person who advocates conservation especially of natural resources. In this thesis, this word can refer to conservation scientist, MPA managers, Non-Governmental Organization, or other structure/person that act for the conservation of natural resources.	Merriam-Webster Dictionary	**C3**-4.3.; **C4**-4.3.; **C5**-4.1., -5.; **D**-1., - 2.1., -2.2., -3.1.1., -3.2.2.
Convention	-	Template outlining the content of a particular maritime law, whilst a law is a statute enacted by a sovereign state.	Stopford, 2009	**I**-1.2.2.; **D**-2.1.
Convention for the Regulation of Whaling	CRW	First international measure of protection for bowhead whales, *Balaena mysticetus*; right whales, *Eubalaena spp.*; and gray whales, *Eschrichtius robustus*; all of which had been heavily exploited historically.	Rocha et al., 2014	**I**-1.1.
Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention)	CMS	Environmental treaty of the United Nations providing a global platform for the conservation and sustainable use of migratory animals and their habitats.	CMS website	**I**-2.2.1.
Convention on the International Regulations for Preventing Collisions at Sea	COLREG	IMO convention setting out navigation rules to be followed by ships and other vessels at sea to prevent collisions between two or more vessels.	IMO website	**C1**-2.2; **C5**-1.
Cost-Benefit Analysis	CBA	Method of evaluating the favorable effects of policy actions and the associated opportunity costs of these actions. It answers the question of whether the benefits are sufficient for the gainers to potentially compensate the losers, leaving everyone at least as well off as before the policy.	U.S. EPA, 2014	**C1**-2.5.1; **C2**-4.4.; **C5**-1., -3.2., -4.3.2.; **D**-1.
Cost-Effectiveness Analysis	CEA	Method of evaluating the costs associated with obtaining an additional unit of an environmental outcome. It is designed to identify the least expensive way of achieving a given environmental quality target, or the way of achieving the greatest improvement in some environmental target for a given expenditure of resources.	U.S. EPA, 2014	**C1**-2.5.1; **C2**-4.4.; **C5**-1., -3.1., -3.2., -4.3.2.; **D**-1., -3.2.1., -3.2.2.
Cost-Effectiveness criterion	-	Maximum acceptable incremental cost-effectiveness ratio acceptable to decision-maker. The criterion gives insights to the decision-makers on if the cost *"is not grossly disproportionate to the reduction in risk that they achieve"*. Beyond this threshold, the RCO will not be adopted.	Culyer, 2010; Det Norske Veritas, 2001	**C1**-2.5.2.; **C5**-3.2.
Cost-Effectiveness ratio / index	-	Statistic used in cost-effectiveness analysis to summarise the cost-effectiveness of a solution.	In this thesis	**C1**-2.5.1.; **C5**-3.1., 3.2.

Critical Reference Point	CRP	Management rule established in 1991 by the IWC for the Western North Atlantic harbor porpoise population. Since then, it is used as a default management rule when other more elaborate ones are not available (e.g., PBR).	Caswell et al., 1998	**C4**-2., -3.2., -4.1., -4.3.; **D**-3.2.1.
Deadweight tons	DWT	Measure of how much mass or weight of cargo or burden a ship can safely carry and includes the weight of the crew, passengers, cargo, fuel, ballast, drinking water, and stores.	Euro Maritime	**I**-1.2.2; **C2**-3.2
Dolphin	-	Marine mammal belonging to the Cetacea infraorder, and to the parvorder of the Odontoceti (toothed whale).	In this thesis	**I**-1.2.1
Draught	-	Depth of water a ship draws, especially when loaded.	Merriam-Webster Dictionary	**I**-2.2.1; **C2**-3.1.
Economies of scale	-	Theory of the relationship between the scale of use of a properly chosen combination of all productive services and the rate of output of the enterprise.	Stigler, 1958	**I**-1.2.2
Ecosystem service	-	Contributions that ecosystems make to human well-being.	Common International Classification of Ecosystem Services	**C5**-4.1.1., -5.; **D**-3.2.2.
Effective	-	Producing a decided, decisive, or desired effect.	Merriam-Webster Dictionary	**I**-2.2.2.; **C1**-2.4., -2.5.; C5-1.; **D**-1., -3.2.3.
Effectiveness	-	Degree to which something is effective.	Cambridge Dictionnary	**I**-2.2.2.; **C1**-2.3., -2.4.; **C3**-1., -4.4.; **C5**-1.
Effectiveness *(Applied)*	-	Degree to which something is effective with constraints (e.g., economic, logistical, law, incentive).	In this thesis	**I**-2.2.2., -3.1.; **C1**-2.4. **C3**-1., -4.2.; **C5**-1.; **D**-2.1., -3.2.2.
Effectiveness *(Theoretical)*	-	Degree to which something is effective without constraint (e.g., economic, logistical, law, incentive).	In this thesis	**I**-2.2.2., -3.1., -4.1.; **C3**-1., -4.2.; **C5**-1.; **D**-3.2.2.
Efficiency	-	Effective operation as measured by a comparison of production with cost (as in energy, time, and money).	Merriam-Webster Dictionary	**I**-4.1.; **C1**-2.4.; **C5**-3.1.; **D**-3.2.2.
Encounter rate theory	-	Encounter rates are proportional to a power of the encounter radius, to the density of particles, and to some combination (e.g., root-mean-square) of the movement velocities (Hutchinson and Waser 2007). These equations were generalized to a predator-prey type scenario by Gerritsen and Strickler (1977) and laterrefined by Evans (1989).	Gurarie and Ovaskainen, 2013	**I**-2.2.1.
Entanglement	-	Refers to the wrapping of lines, netting, or other materials of anthropogenic origin around the body of an animal.	IWC, 2010	**I**-1.2.1; **C4**-1., -3.1., -4.1., -4.2., -4.3.; **D**-1.
Environmental Kuznets Curve	-	Hypotheses that (1) there is a basic conflict between economic growth and environmental protection, but (2) the basic conflict is resolved when enough economic growth occurs.	Czech, 2003	**I**-1.1.
Federal Aviation Administration	FAA	Governmental body of the United States with powers to regulate all aspects of civil aviation in that nation as well as over its surrounding international waters.	FAA Website	**C2**-4.1.; -4.4.

Formal Safety Assessment	FSA	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	IMO, 2018	**I**-4.2; **C1**-1., -2., -3.; **C2**-1., 4.4.; **C4**-4.3.; **C5**-1., -2.2., -3., -4.3.1., -4.3.2.; **D**-1., -3.1.1., -3.1.2., -3.2.1., -3.2.2., -3.2.3.,
Freedom of the seas	-	Principle in the international law stating the right of a merchant ship to travel any waters except territorial waters either in peace or war. This principle was limited by the Law of the Sea treaty (UNCLOS).	Merriam-Webster Dictionary	**I**-1.2.2.
Frequency	-	Number of occurrences per unit time (e.g., per year).	IMO, 2018	**I**-2.2.1.; **C1**-2.3., -2.5.2.; **C5**-2.3.1.
Global Integrated Shipping Information System	GISIS	IMO semi-public database.	GISIS website	**C2**-4.4.
Gross Tonnage	GT	Term used to describe a ship's total internal volume, whereas 1 GT is equal to 100 cubic feet.	Euro Maritime	**I**-1.2.2.
Hazard	-	Potential threat to human life, health, property or the environment.	IMO, 2018	**C1**-2.2.
Human Induced Direct Mortality	HIDM	Annual removal directly after a human-whale interaction, such as collisions, whaling or entanglement.	In this thesis, modified from Thomas et al., 2016 and from IWC, 2009	**I**-1.; **C4**-1., -2., -3., -4.; **C5**-2.2.3., -3.2., -4.1.2.; **C5**-1.
Human Induced Indirect Mortality	HIIM	Annual removal indirectly linked to human activities, such as anthropogenic noise, physical and chemical pollution, prey depletion due to overfishing and climate change.	In this thesis	**I**-1.; **C4**-1., -4.
Human Induced Mortality	HIM	Magnitude of annual removals from a stock due to incidental catch and other directed human causes / Annual removals from a stock due to human activities.	Wang et al., 1994 / In this thesis	**I**-1.; **C4**-1.
International Civil Aviation Organization	ICAO	United Nations Agency *"whose mission is to achieve safe, secure, and sustainable development of civil aviation"*.	ICAO, 2017	**I**-3.2.2.; **C2**-4.1; -4.4; **D**-2.1.
International Conference on Marine Mammal Protected Areas	ICMMPA	International conference focusing on the challenges ahead to examine concrete and practical steps towards achieving effective place-based protection and management for marine mammals.	ICMMPA website	**I**-2.2.1.; **C1**-1.; **C3**-4.2.; **C4**-3.1.
International Convention for the Regulation of Whaling	ICRW	Convention conveying a legally binding Schedule, which, amongst other things, sets out catch limits for commercial and aboriginal subsistence whaling.	IWC website	**I**-1.1
International Maritime Organization	IMO	United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.	IMO website	**I**-1.2.2.; **C1**-1., -2., -3.; **C2**-1., -2.2., -4.3., -4.4., -5.; **C3**-4.2.; **C4**-4.3.; **C5**-1., -3., -5.; **D**-1., -2., -3.
International Monetary Fund	IMF	Organization of 189 countries, working to foster global monetary cooperation, secure financial stability, facilitate international trade, promote high employment and sustainable economic growth, and reduce poverty around the world.	IMF Website	**C5**-5.
International Observer Scheme	-	Scheme to place observers on whaling vessels and shore whaling stations.	UK National Archives	**I**-1.1.

International Union for Conservation of Nature	IUCN	International association of governmental and non-governmental members, which aims to *"to influence, encourage and assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable"*.	IUCN, 2019	**I**-2.2.1.; **C4**-1., -4.1., -4.2., -4.3.; **D**-1., 3.2.1.
International Whaling Commission	IWC	Global body charged with the conservation of whales and the management of whale hunting. The Commission works to promote the recovery of depleted whale populations by addressing a range of specific issues, while keeping whale catch limits under review. These include ship strikes, entanglement events, environmental concerns and establishing protocols for whale watching.	IWC website	**I**-1.; -1.1.; -1.2.2.; **C1**-1.; **C2**-1, -2.1., -2.2., -2.3. -4.2., -4.4.; **C4**-4.3.; **D**-3.2.1.
Law of the Sea	-	International agreement under the United Nations, which defines the rights and responsibilities of nations with respect to their use of the world's oceans. The law of Seas provides a *"comprehensive framework for the regulation of all ocean space […] the limits of national jurisdiction over ocean space, access to the seas, navigation, protection and preservation of the marine environment"*.	Finley, 2016; United Nations, 1983 in Stopford, 2009.	**I**-1.2.1.
Limit Reference Point	LRP	Removal thresholds to undesirable population or ecosystem states.	Curtis et al., 2015	**C4**-1.; **C5**-2.2.; **D**-1.
Management rules	-	Conservation targets that influence policy decisions (e.g., Limit Reference Points)	In this thesis	**I**-1.2.1.; **C4**-1., -2., -3.2., -4.1., -4.3.; **C5**-2.2.; **D**-1., -3.2.1.
Marine mammal	-	Group of animals with a combination of characteristics that separate them from all others: warm-blooded, have hair or fur, breathe air through lungs, feed underwater, bear live young, and nurse their young with milk produced by mammary glands. Marine mammals are classified into four different taxonomic groups: cetaceans (whales, dolphins, and porpoises), pinnipeds (seals, sea lions, and walruses), sirenians (manatees and dugongs), and marine fissipeds (polar bears and sea otters).	Modified from various sources	**I**-1.2.1., -2.2.1., **C1**-2.3., **C3**-1.; **C4**-1.; **C5**-2.2., 2.3.1.; **D**-2.2.
Marine Mammal Protected Areas	MMPA	Specially managed protected areas (PAs) that contribute to the protection of marine mammals and their habitat.	Notarbartolodi Sciara et al., 2016	**I**-2.2.1.
Marine Protected Areas	MPA	Any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment.	Jones, 2002	**I**-2.2.1; **C4**-1., -4.1.; **D**-2.1.
Maximum Sustained Yield	MSY	Theoretical concept used extensively in fisheries science and management. It represents the maximum catch (in numbers or mass) that can be removed from a population over an indefinite period.	Maunder, 2008	**I**-1.2.1.
National Oceanic and Atmospheric Administration	NOAA	American scientific agency within the United States that focuses on : 1. Understanding and predict changes in climate, weather, oceans and coasts; 2. Sharing that knowledge and information with others; and 3. Conserving and managing coastal and marine ecosystems and resources.	NOAA Website	**D**-3.2.1.
Operational mitigation solution	-	Measures that involve a change in the way ships navigate to reduce whale-ship collisions.	In this thesis	**I**-2.2.2; **C1**-2.4; **C3**-1.; **C5**-1.
Passenger ships	-	Specialized passenger transportation ships, but also Ro-Ro ship, which may carry human and non-human merchandise (e.g., cars).	In this thesis	**I**-1.2.2; **C2**-2.3;-3.2; **C3**-4.1., -4.3.; **D**-1.
Pelagos Sanctuary	-	Specially protected area under the Barcelona Convention that aims to protect marine mammals from all sources of disturbance caused by human activity	Pelagos Sanctuary website	**I**-2.2.1; **C4**-1.; -4.1., -4.3.; **D**-1., 2.1.

Population Viability Analysis	PVA	Process aiming to evaluate the likelihood that a population will persist in the future.	Boyce, 1992	**C1**-2.3.
Potential Biological Removal	PBR	Management rule corresponding to *"the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population"*.	Wade, 1998	**C1**-2.3.; **C4**-2., -3.2., -4.3.; **C5**-2.3., -3.2., -4.1.2.; **D**-3.2.1.
Protected Area	PA	Clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.	IUCN, 2012	**I**-2.2.1.
REPérage en temps réel des CETacés	REPCET	Device aiming at limiting the risk of collisions between large cetacean and ships.	Couvat et al., 2014	**I**-2.2.2.; **C1**-1., -2.2.; **C3**-1., 2.1., -4.2.; **C4**-1.; **C5**-3.2.; **D**-1., 2.1.
Risk	-	Combination of the frequency and the severity of the consequence.	IMO, 2018	**I**-1.2., -2.1., -2.2.2., -3.1., -3.2.2., -4.; **C1**-1., -2., -3.; **C2**-1., -2.3., -3.2., -4.1., -4.2., -4.4., -5.; **C3**-1., -4.1., -4.2.; **C4**-4.1., -4.3.; **C5**-1., -3., -4.3.2.; **D**-1., -3.1.1., -3.2.1., 3.2.2.
Risk Control Measure	RCM	Means of controlling a single element of risk.	IMO, 2018	**C1**-2.4;
Risk Control Option	RCO	Combination of risk control measures.	IMO, 2018	**C1**-2.4.; **C5**-1.
Risk Evaluation Criteria	-	Tools for decision-making that *"define how risks are measured (metric), the level of risks that are acceptable and the level of investment in risk reduction that are deemed necessary"*. In this thesis, the cost-effectiveness criterion in Chapter 1 represents a risk evaluation criterion. According to the FSA guidelines, a way of estimating the cost-effectiveness criterion is to assess the willingness to pay to avert a fatality. This method is used to define the cost of averting a whale fatality in Chapter 5, which can be used as a risk evaluation criterion.	Skjong et al., 2005	**I**-4.2.; **C5**-1.,-3., -4., -5.; **D**-1., -2.2., -3.2.2.
Speed reduction	SR (C1) / SRS (C3)	Mitigation solution resulting in the reduction of the probability of lethal collision	In this thesis	**I**-4.2.; **C1**-1., -2.4., -3.; **C2**-3.1., -4.2.; **C3**-1., -2.1., -3.2.1., -4.1., -4.2., -4.3.; **C4**-4.3.; **C5**-1.; **D**-1.
Status *(Conservation status)*	-	Degree to which a species or population is at risk of extinction.	Barlow, and Reeves, 2009.	**I**-2.2.1.; **C4**-1., -4.1., -4.3.; **C5**-2.1., -2.3.1., -4.3.2.; **D**-1.
Stranding network		Regional teams that respond to the stranding of marine mammals and are equipped to collect biological information and samples that can be used to understand the health, population dynamics, and life histories of marine mammals. Mediterranean Stranding Networks are referred to as MSN in Chapter 4.	Becker et al., 1994	**I**-1.2.2.; **C1**-2.3.; **C4**-2.; **D**-1.
Tanker	-	Ship specialized in oil and chemical transportation.	In this thesis	**I**-1.2.2.; **C2**-2.3., -3.2.; **C3**-2.2., -2.3., -3.1.
Technical mitigation solution	-	Control measures that aim to better detect whales.	In this thesis	**I**-2.2.2.; **C1**-2.4.; **C3**-1.; **C5**-1.; **D**-1., -2.2.
Traffic Separation Scheme	TSS	Mitigation solution resulting in the reduction of the probability of collision.	In this thesis	**I**-2.2.2.; **C1**-2.4.; **C3**-1., -4.1., -4.2.; **D**-3.1.2.

U.S. Marine Mammal Protection Act	U.S. MMPA	U.S. Law prohibiting, with certain exceptions, the "*take*" of marine mammals in U.S. waters and by U.S. citizens on the high seas, and the importation of marine mammals and marine mammal products into the U.S.	U.S. Fish and Wildlife Service Website	**C**4-4.3.; **C5**-2.3.1.; **D**-3.2.1.
United Nations Convention on the Law of the Sea	UNCLOS	Comprehensive regime of law and order in the world's oceans and seas establishing rules governing all uses of the oceans and their resources.	United Nations Website	**I**-1.2.2.; **D**-3.1.2.
Whale	-	Large, aquatic, marine mammals (order Cetacea) that have a torpedo-shaped body with a thick layer of blubber, paddle-shaped forelimbs but no hind limbs, a horizontally flattened tail, and nostrils that open externally at the top of the head. The term whale is often attributed to Mysticety (baleen whales). In this thesis, whales refer to baleen whales and sperm whales, as they share physiological traits that make them vulnerable to ship strikes.	Merriam-Webster Dictionary	**I**; **C1**; **C2**; **C3**; **C4**; **C5**; **D**
Whaling	-	Industrial harvest of whales for commercial use.	Modified from Roman et al.,2014	**I**-1.1.; **D**-3.1.1.
World Wildlife Fund	WWF	International non-governmental organization to mobilize support for conservation, especially from the general public.	WWF website	**I**-2.2.1.

DOCTORAT BRETAGNE LOIRE / SCIENCES DE LA MER ET DU LITTORAL

UBO
Université de Bretagne Occidentale

Titre: Une approche interdisciplinaire à la gestion des collisions entre navires et baleines

Mots clés: collision navire-baleine; Organisation Maritime Internationale; Évaluation Formelle de la Sécurité; Évaluation des risques; préférences logistiques; coûts évités.

Résumé: Les collisions avec des navires sont l'une des principales menaces modernes à la survie des baleines. Plusieurs solutions existent pour réduire le risque de collision, mais la mise en conformité de l'industrie du transport maritime avec ces solutions est souvent limitée. Cette thèse interdisciplinaire vise à comprendre les lacunes économiques, logistiques et écologiques qui entravent cette mise en conformité. La question de recherche est la suivante: comment intégrer les dimensions humaines et écologiques dans un processus standardisé pour mieux gérer les collisions baleines-navire? Pour répondre à cette question, cette thèse vise à (1) définir un processus d'évaluation standardisé des solutions de réduction du risque; (2) d'étudier les dimensions économiques et logistiques nécessaires pour réaliser une évaluation globale du problème des collisions entre les baleines et les navires. L'Organisation Maritime Internationale a le potentiel d'améliorer la protection des baleines contre les collisions avec les navires, et nous étudions son cadre d'évaluation des risques, à savoir l'Evaluation Formelle de la Sécurité. Sur la base des lacunes identifiées dans ce cadre, notre recherche explore d'abord la notion de risque acceptable dans l'industrie du transport maritime et dans la science de la conservation. Ensuite, nous étudions les préférences de l'industrie du transport maritime pour les solutions de réduction du risque et étudions les avantages économiques d'éviter les collisions, à travers les coûts évités et les critères d'évaluation des risques. En créant un pont entre l'économie et l'écologie, cette thèse améliore la compréhension mutuelle de l'industrie du transport maritime et des sciences de la conservation. Ces travaux peuvent servir de lignes directrices pour la proposition de solutions, conduisant à une mise en conformité accrue des compagnies maritimes et, par conséquent, à une meilleure protection des baleines.

Title: An interdisciplinary approach to the management of whale-ship collisions

Keywords: whale-ship collision; International Maritime Organization; Formal Safety Assessment; risk assessment; logistical preferences; avoided costs.

Abstract: Collisions with ships are one of the main modern threats to whale survival. Several solutions exist to reduce the risk of collision, but the compliance of the shipping industry with them is often limited. This interdisciplinary thesis aims at understanding the economic, logistic, and ecological gaps that hinder the shipping industry's compliance. The research question is the following: How to integrate human and ecological dimensions in a standardized process to better manage whale-ship collisions? To answer this question, this thesis aims at (1) defining a standardized assessment process for mitigation solutions; (2) investigating the economic and logistic dimensions needed to achieve a holistic assessment of the whale-ship collision issue. The International Maritime Organization has the potential to improve whale protection from ship strikes, and we investigate its risk assessment framework, namely the Formal Safety Assessment. Based on the identified gap within this framework, our research first explores the notion of acceptable risk within the shipping industry and conservation science. Then, we investigate the preferences of the shipping industry for mitigation solutions, and study the economic benefits of avoiding collisions, through avoided costs and risk evaluation criterion. By creating a bridge between economics and ecology, this manuscript improves the mutual understanding of the shipping industry and conservation science. This work could be used as guidelines for the proposal of solutions, leading to an increased compliance of the shipping companies, and, therefore, an improved protection of whales.