A proposed framework for managing environmental causes and consequences of ocean traffic and ports

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Abstract

The cumulative and in-combination effects of ocean shipping and port operations need addressing via a detailed, rigorous and holistic framework of risk assessment and risk management. This aims to protect the natural system while at the same time obtaining societal benefits from the seas. This paper proposes a conceptual framework that integrates both an ISO industry standard risk assessment and management framework (Bow-tie analysis) and the DAPSI(W)R(M) analysis supported by the ten-tenets criteria to provide guidance for all stakeholders, including industry and government, to address these issues. Water pollution stemming from maritime logistics and SCM are used to illustrate this framework.

Keywords: Ocean Pollution, Logistics and Supply Chain Management, Ten Tenets, DAPSI(W)R(M) Problem Structuring, Bow-tie Analysis

Introduction

All of industry and users of the environment have to demonstrate that their activities are environmentally sustainable and that they fulfil all relevant national and international legislation protecting the environment (Boyes and Elliott, 2014). It is axiomatic that an industry has to prove that it is not harming the environment whereas an environmental regulatory body does not have to prove that an industry is harming the environment (McLusky and Elliott 2004). In defining and tackling environmental problems and potential problems industry essentially has to perform a risk assessment and risk management approach (Cormier et al, 2013). This requires a robust and legally defensible approach irrespective of whether the activity is building a new power plant or operating a vessel in coastal waters. Once an activity has been determined as causing an environmental effect then there is the need to enable a management approach involving problem-alleviation measures. This requires a sound conceptual framework based on good science and fit-for-purpose approaches.

We introduce in this paper a conceptual framework to provide guidance for businesses and their stakeholders, including government, to address these issues. We use pollution and other environmental effects in the logistics and Supply Chain Management (SCM) of ocean lane shipping and transport in the Baltic Sea to illustrate the use of this framework.

This paper is structured as follows. First, we review the literature to consider environmental effects on water stemming from ocean lane shipping and transport and ships resident in port developments, particularly in the Baltic Sea as operative causes with certain consequences for the framework. We next define, describe and discuss the inter-linked elements underlying the framework: the ten tenets of sustainable management stakeholder consultation criteria (Barnard and Elliott, 2015), the DAPSI(W)R(M) (**D**rivers-**A**ctivities-**P**ressures-**S**tate changes-**I**mpacts (on human **W**elfare)-**R**esponses (as **M**easures)) problem structuring method (Wolanski and Elliott, 2015), and the Bow-Tie risk assessment and management analysis approach that integrates the other two elements (Cormier et al 2013). Then, we present an integrated, conceptual framework with some observations as how to it could be implemented in our example of ballast water discharges. Finally, we draw conclusions and provide suggestions for future research to further develop this concept.

Literature Review

Effects of increased logistics on the marine environment – the size of the problem

Halpern et al (2008) illustrated the degree of activities on the world's oceans and many studies have identified the large number of sea-area users (e.g. Boyes et al, 2007). Of these, shipping and its associated activities are a major concern. Tournadre (2014) analysed global ship density using altimeter data and found a dramatic fourfold increase of traffic between the early 1990s and 2014. The only region where there was a decline of traffic is located near Somalia and is related to piracy starting in 2006–2007. The distribution of growth over different ocean basins reflects the redistribution of the international trade with the largest growth in the Indian Ocean and the Western Pacific Seas.

Ocean or short-sea shipping is well-suited for the intercontinental shipment of bulk cargo, bulky goods, containers and dangerous materials such as oil and gas over large distances. Its strengths include being very economic, environmentally-friendly as regards carbon dioxide (CO_2) emissions per tonne of cargo despite bunker fuel being a particularly 'dirty' fuel, handling very large transport volumes, and operating independent of weather conditions. As a result of globalization, container trade has increased on average 5% per year over the last twenty years and is currently around 350 million twenty-foot equivalent (TEU) container movements a year. Container traffic is around 42 million TEU between Asia and Europe and 31 million TEU between Asia and North America. Interestingly, there is 45 million TEU in Intra-Asia, which likely reflects trade between Asian countries related to sub-contracting manufacturing and providing logistics services such as consolidation for other marketplace (Grant, 2012).

The cruise line sector is not as large as the cargo sector however it is estimated that 23 million passengers cruised globally in 2015. At an average of 3,000 passengers per cruise ship that means there are about 7,700 annual cruise ship movements. Annual growth in the sector over the last thirty years is just over 7.2%. As a result, many new, large cruise ships have entered the market and it was forecast that 33 new cruise ships with over 100,000 berths and an investment of US$25 billion were planned for delivery during the period 2015-2020 (F-CCA, 2016).

Finally, there are many scheduled short- and long-haul ferry services worldwide. Holthof (2016) has estimated of the number of ferries around the world as follows: 1,085 large displacement ferries plus 111 freight-only, roll on-roll-off (Ro-Ro) with a capacity exceeding 12 passengers, 222 pure freight Ro-Ro ferries with a capacity of up to 12 passengers, 1,877 lightweight fast craft - 180 with car capacity and 1,697 passenger-only fast craft. He further estimated that the global ferry market carried 2.2 billion passengers, 258 million cars and 39 million Ro-Ro trailers in 2013.

Figure 1 shows the movement of ferries in the Baltic Sea region, excluding long-haul ferry services to the North Sea countries and Spain. Ferry traffic volumes in the Baltic region in 2013 were 238 million passengers, 92 million cars and 12 million Ro-Ro trailers. We now turn to the various environmental effects that this increased movement of ships has on marine areas, i.e. ocean or short-sea shipping lanes and port developments.

Effects of increased logistics on water – environmental issues

The generally accepted major pollution and other environmental effects from ocean and short-sea shipping include CO_2 and sulphur dioxide (SO_2) emissions in ports and at sea, fuel consumption of a non-renewable resources, pollutants from ballast water, sewage and garbage discharges, space occupation that may inhibit natural ecosystem development, acidification of ocean and sea pH levels from CO_2 and SO_2 emissions (OSPAR Commission, 2009). These effects will now be discussed in more detail with reference to the specific example in the horrendogram in Figure 3. This model has been developed from a wide knowledge of the port and navigation activities and their repercussions (e.g. McLusky and Elliott, 2004).

Rigot-Muller et al. (2013) found that end-to-end logistics-related CO_2 emissions can be reduced by 16-21% through direct delivery to a UK port as opposed to transshipment via a Continental European port, i.e. cargo feeder systems. The analysis showed that for distant overseas destinations, the maritime leg represents the major contributor to CO_2 emissions in an end-to-end global supply chain. In that regard, McKinnon (2014) argued that by packing more products into containers shippers could reduce the number of container movements and related CO_2 emissions. The pressure to minimise shipping costs would also give these companies a strong incentive to maximise fill. He surveyed 34 large UK shippers and found that inbound flows into the UK were of predominantly low density products bound for retail stores that 'cubed-out' before they 'weighed-out;' i.e. 46% of respondents importing containerised freight claimed that 90-100% of containers received were 'cubed-out', i.e. to reach the volume limit of the container before reaching the weight limit. McKinnon (2014) also found that only around 40% of shippers have so far measured the ‘carbon footprint’ of their deep-sea container supply chains with just 6% implementing carbon-reducing initiatives. The companies surveyed also assigned a relatively low weighting to environmental criteria in ocean carrier selection. So, while many shippers have the means to influence the carbon footprint of their maritime supply chains, the survey suggested that they are not currently using them explicitly to cut CO_2 emissions.

Figure 1 –Baltic ferry Movements (Source: Holthof, 2014)

Many of the measures that the UK shippers and their ocean carriers are implementing to improve economic efficiency, most notably slow steaming, are assisting carbon mitigation efforts. Slow steaming involves reducing the speed of a ship while at sea to reduce engine load and emissions. Slow steaming was mooted by the Maersk Line as a response to the 2008 economic recession as the spot-market price Maersk Line received in late 2008 for shipping containers from Asia to Europe or North America was around US $500 below their operating costs. The relationship between ship speed and fuel consumption is nonlinear and Maersk Line calculated that by redesigning their shipping schedules, using nine ships instead of eight to ensure customer volumes were handled and slowing the vessel sailing speeds from 22 knots to 20 knots, they could reduce annual fuel consumption from 9,500 to 8,000 metric tonnes (Mt) and thus also reduce carbon emissions 17% from 30,000 to 25,000 Mt of CO_2 (Grant et al, 2015).

Only a small number of UK ports actually measure and report their carbon emissions. Emissions generated by ships calling at these ports were analysed by Gibbs et al. (2014) and indicated that emissions generated by ships during their voyages between ports are of a far greater magnitude than those generated by port activities. However, 70% of shipping emissions occur within 400 km of land; thus ships contribute significant pollution in coastal communities. Shipping-related particulate matter (PM) emissions have been estimated to cause 60,000 cardiopulmonary and lung cancer deaths annually with most deaths occurring near coastlines in Europe, East Asia and South Asia (Corbett et al., 2007; Winebrake et al., 2009).

Rising concentration of CO_2 in the atmosphere results in a slow acidification of the surface ocean (Elliott et al, 2015). Anthropogenic acidification from emissions of sulphur and nitrogen oxides (SO_x, NO_x) creates acidification and eutrophication of land and freshwater ecosystems and in terms of atmospheric aerosol effects on regional and global climate, but deposition also occurs over ocean surfaces in the form of sulphuric and nitric acids. Since the late 1990s international shipping has been recognized as a significant contributor of SO_x and NO_x to the atmosphere on local, regional, and global scales. However, the problem is less significant in the Baltic Sea compared to the Pacific Ocean and elsewhere in Asia (Hassellöv et al., 2013).

Furthermore, sulphur emissions as part of overall shipping-related particulate matter emissions is a problem for ships in port. Around 18 shipping lines signed the Fair Winds Charter in 2010, which is an industry-led, voluntary, unsubsidised fuel switching programme for ocean-going vessels calling at Hong Kong. The shipping lines are using fuel of 0.5% sulphur content or less although they all switched to the cleanest type of fuel available with 0.1 % sulphur, SO_2 emissions would drop by 80%. In return, ship operators get a 50% reduction on port and navigation charges if registered vessels switch to burning low-sulphur diesel while berthed or anchored in Hong Kong. However, low sulphur diesel is about 40% more expensive than more heavily polluting marine ‘bunker’ diesel and the scheme only covers between 30 and 45% of this higher cost. Thus, while shipping companies including Maersk Line, Orient Overseas Container Line (OCCL), Mitsui OSK Lines and Hyundai Merchant Marine have registered fleets of 10-90 ships, other cost-conscious carriers have been more reticent. APL and Hanjin Shipping were among the companies that signed the Fair Winds Charter, but neither has registered any ships with the incentive scheme (Grant et al, 2015).

Such chemical discharges to the environment are defined as contamination unless they cause a biologically harmful effect, in which case they are defined as pollution (Gray and Elliott, 2009). More recently, the introduction of organisms has also been regarded as both contamination and pollution (Elliott, 2003). Hence, after almost two decades of intensified research, regulatory and political activities focussed on the prevention of harmful organisms and pathogen transfers around the world (Olenin et al., 2011). In 2004 the International Convention on the Management of Ships’ Ballast Water and Sediments was adopted to provide a common and globally uniform approach to ballast water management (BWM). However, regionally different BWM approaches have developed. However, BWE (ballast water exchange, en route) as a BWM tool is seen as an interim solution as scientific studies have proven its limited effectiveness, in addition to the fact that the water depth and distance from shore requirements as set forth in the BWM Convention cannot be met in many circumstances (David and Gollasch, 2008). One possible solution is the adoption of a Creation of Shared Value (CSV) concept whereby all stakeholders buy-in to the sustainability goals for issues such as BWM (Aravossis and Pavlopoulou (2013).

Since the 1970s, the EU has developed many Directives for controlling the harmful effects of marine activities (Boyes and Elliott 2014). These are implemented by Member States and enforced through local and national enabling legislation. For example, while a Member State has to comply with pollution control required by the EU Directives, otherwise it gets reported to the European court, controlling discharges within its environment is under national legislation such as pollution control regulations which can lead to companies being fined. Hence it is important that businesses are aware of the legislation and are complying with it.

Scharin et al (submitted) show that the multi-use Baltic Sea has cumulative effects which require a complex assessment and management system. Its enclosed nature confers a poorer ability to purify than more open systems and hence increased environmental challenges, covering larger areas and lasting a longer period. As an example, Lehmann et al. (2014) identified areas in the Baltic Sea from where potential pollution is transported to vulnerable regions. They found that in general there is higher risk of ship accidents along the shipping routes and along the approaching routes to harbours, and that the spreading of harmful atmospheric substances is mainly controlled by prevailing atmospheric conditions and wind-induced local sea surface currents. Using sophisticated high resolution numerical models, they simulated the complex current system of the Baltic Sea, and with subsequent drift modelling areas of reduced risk or high-risk areas for environmental pollution could be identified. Lehmann et al. (2014) considered that the receiving areas of fish spawning and nursery areas and tourist areas are highly-vulnerable.

Thus corporate strategic decision-making for shippers and ocean shipping lines creates challenges when it comes to sustainability in the face of thin profit margins, rising fuel and other operating costs and global economic uncertainty. However, because of environmental controls, a sustainability risk strategy is required, particularly in the shipping industry (Kun et al., 2015)

Development of a framework for analysis

Given these constraints, a company selects a framework or technique to include sustainability into its corporate strategy including the need to assess such matters as the economic viability, technological feasibility and environmentally sustainability of that strategy. Some tools and techniques currently exist, however they are focussed on discrete situations and events or are not holistically inclusive. For example, Lam and Lai (2015) used an approach that integrates Analytical Network Process (ANP) and Quality Function Deployment (QFD) to illustrate how shipping companies can undertake a customer cooperation programme and achieve sustainability in their operations through CO_2 emission reductions.

However, Borja and Dauer (2008), while noting that many methodologies with hundreds of indices, metrics and evaluation tools are currently available, noted that in order to deal with the complexities of socio-environmental issues, many countries have adopted the DPSIR (Drivers-Pressure-State-Impact-Response) framework (Atkins et al., 2011). DPSIR is an environmental management paradigm as a feedback loop system in which driving forces (D) of social and economic development exert pressure (P) on the environment thereby changing its state (S), potentially resulting in impacts (I) on human health and/or ecosystem function that may elicit an environmental management response (R). Economic development, such as a port expansion, will invariably increase environmental pressures, some of which will be ameliorated through specific management actions.

For example, increasing a port area will cause the loss of estuarine habitats such as mudflats or salt marshes or disturb overwintering wading birds or fishes such as eels and salmon migrating between the sea and the catchment (McLusky and Elliott, 2004). Such relationships between society and in this case logistics and SCM impacts on the environment, and responses to such impacts, can be formalised through the development of the DPSIR systems-based approach (Atkins et al., 2011).

The ten tenets criteria of environmental management

Integrated environmental management requires many aspects to be combined into a holistic system (Elliott 2014). The problems caused by materials (e.g. pollution) or infrastructure added to the system or removed from the system (e.g. aggregates, wetland space) require a risk assessment framework. This is then managed using the actions through vertical integration of governance and the horizontal integration of stakeholder action. Those actions are required to ensure the natural system is protected and maintained while at the same time the benefits required by society are delivered. Such a combined framework and set of tools is then termed the Ecosystem Approach (Elliott 2014).

Consideration of these interactive environmental relationships gives rise to assessing whether the strategy or strategic option fulfils various criteria related to environmental management. Elliott (2013) proposed the ‘ten tenets’ of environmental management to facilitate such assessment so that management of and a solution for an environmental problem will be sustainable and not environmentally deleterious. Further, they should fall within what is possible in the real world while taking note of the socio-economic and governance aspects. Finally, fulfilling the ten tenets would also mean that environmental management would potentially be seen by wider society as achieving sustainability and in turn would be more likely to be accepted, encouraged and successful. The ten tenets are listed in Table 1 and are self-explanatory although Barnard and Elliott (2015) interrogate and quantify these further for port and marina operations. . We now turn to setting and structuring of environmental problems using a revision of the DPSIR approach: the DAPSI(W)R(M) method (pronounced *dapsiworm*).

Table 1 – The Ten-Tenets of Environmental Management (Source: adapted from Elliott, 2013 and Barnard and Elliott 2015)

Socially desirable/tolerable: Environmental management measures are required or at least are understood and tolerated by society as being required; that society regards the protection as necessary.

Ecologically sustainable: Measures will ensure that the ecosystem features and functioning and the fundamental and final ecosystem services are safeguarded.

Economically viable: A cost-benefit assessment of the environmental management indicates (economic/financial) viability and sustainability.

Technologically feasible: The methods, techniques and equipment for ecosystem and society/infrastructure protection are available.

Legally permissible: There are regional, national or international agreements and/or statutes which will enable and/or force the management measures to be performed.

Administratively achievable: The statutory bodies such as governmental departments, environmental protection and conservation bodies are in place and functioning to enable successful and sustainable management.

Politically expedient: The management approaches and philosophies are consistent with the prevailing political climate and have the support of political leaders.

Ethically defensible: How costs of acting are determined and calculated for current and future generations.

Culturally inclusive: Notwithstanding actions are desired and tolerated by society there may be some cultural considerations taking precedence.

Effectively communicable: Communication is required among all the stakeholders to achieve the vertical and horizontal integration encompassed in the foregoing nine tenets.

The DAPSI(W)R(M) problem structuring method

There were some anomalies in the DPSIR approach that have been rectified in a new, enhanced DAPSI(W)R(M) approach (Wolanski and Elliott, 2015; Burdon et al., in press; Elliott et al., submitted), and which we adopt here for this paper. The Drivers of basic societal needs (D) remain the same however they now requires Activities of society (A) that in turn generate the Pressures resulting from these activities (P). The Pressures are mechanisms that effect a State change on the natural system (S) that in turn generates Impacts on human Welfare (I(W)) that are changes affecting wealth creation and quality of life. These revised Impacts on human Welfare lead to Responses that can be verified as Measures (R(M)).

The ten-tenets relate to actions or management measures that are important for all stakeholders and are available from and carried out by the relevant stakeholders. Within the DAPSI(W)R(M) approach, State changes and Impacts on human Welfare together represent the changes to the receiving environment, direct human interaction with the environment is represented not just by Responses and Measures, but also by the Drivers as the demands on the system leading to the Activities causing the Pressures.

The ten tenets for sustainable management predominantly apply to society and the economy rather than the natural environment; Barnard and Elliott (2015) emphasise that nine out of the ten have a societal and economic basis. Hence the assessment of environmental change is not restricted solely to natural environmental aspects of the Pressures (i.e. the management measures introduced in response to the State changes) but also to the human consequences (i.e. the Impacts on human Welfare). In essence, we assess the Pressures, State changes and Impact (on human Welfare) but we manage the Drivers and Activities. Indeed, 'environmental management' can be regarded as a misnomer in that we are not managing the environment but rather the people and their actions. For example, we assess the change to the seabed during port dredging but we manage the dredging frequency, intensity, extent and duration.

The Bow-Tie analysis

To integrate the DAPSI(W)R(M) approach and the ten-tenets criteria we adopt the Bow-tie risk management analysis as shown conceptually in Figure 2. Fault tree analysis (FTA) and event tree analysis (ETA) have been used for risk assessment for many years. However, these techniques share a common objective, which is to provide an assurance that a process or a system is designed and operated under an 'accepted risk' or a 'threshold' criterion together. Both FTA and ETA can be used together in what is known as a bow-tie analysis (Ferdous et al., 2012; Cormier et al, 2013). FTA provides a graphical relationship between the undesired event and basic causes of such an occurrence while ETA is a graphical model of consequences that considers the unwanted event as an initiating event and constructs a binary tree for probable consequences with nodes representing a set of success or failure states. The follow-up consequences of the initiating event in ETA are usually termed as events or safety barriers, and the events generated in the end states are known as outcome events.

Both techniques use the probability of (e.g. failure or success) basic events and events as quantitative inputs and determine the probability of occurrence for the top-event as well as outcome events for likelihood assessments. The ISO industry standard (IEC/ISO 2009) Bow-tie analysis has been long used in industries especially those constructing and operating new plant such as power stations (Cormier et al., 2013). It is a combined concept that integrates both techniques in a common platform, considering the top-event and initiating event as linked to a common event called a critical event. Like FTA and ETA, Bow-tie analysis also uses the probability of failure of basic events as input events on the FTA site and the probability of occurrence (either failure or success) of events as input events on the ETA site for evaluating the likelihood of critical and outcome events. For quantitative Bow-tie analysis the probabilities of input events are required to be known either as precise data or defined probability density functions (PDFs) if uncertainty needs to be considered. If such quantitative information is not known then an expert judgement approach can be taken although of course this may produce only a semi-qualitative set of outcomes.

As with any risk assessment and risk management approach, the Bow-tie analysis method is initially a qualitative model for displaying links between causes, hazards and consequences, but can be further developed with quantitative modelling. For example, Baysian Belief Network modelling based on probabilities of cause and effect has recently been linked to Bow-tie analysis (Stelzenmüller et al 2014; ICES, 2015). By linking this method to a DAPSI(W)R(M) approach based on ten-tenets criteria, it enables scoping, identification and analysis of:

i) the causes (based on the Drivers, Activities and Pressures) leading to the main events;
ii) anticipatory prevention measures (the Responses using Measures), including those limiting the severity of the main event;
iii) the consequences of the events (the State Changes and the Impacts on human Welfare), and
iv) mitigation and compensation measures (i.e. the Responses using Measures) aimed at minimising those consequences (Burdon et al., 2015).

Figure 2 shows a conceptual Bow-tie analysis model for *inter alia* three potential environmental issue causes related to ocean and short-sea transport and docking at port. As a subset of environmental causes from Figure 1, examples of these causes could be CO_2 and SO_2 emissions into the water (A), ballast water discharges into the water while in port (B), and acidification (C). Consequences of these causes could include *inter alia* high levels of biological pollutants in the receiving environments (water and sediment); (E), harmful air emissions around the ship (F), and an increase in human illness and disease as a result of increased emissions, discharges and acidification (G).

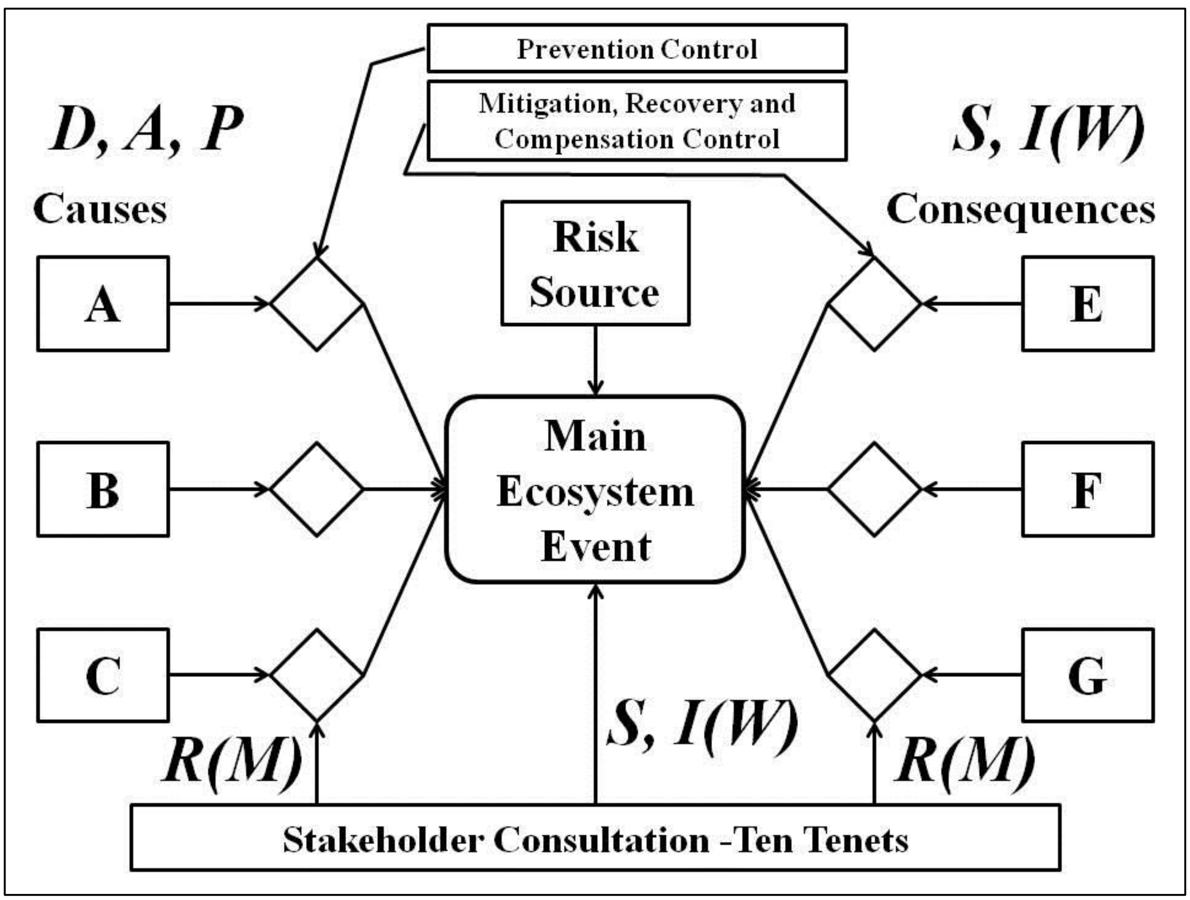

Figure 2 –Proposed Framework

Specific application related to ballast water discharges

For simplicity of explanation we select only one cause, ballast water discharges (B), for further analysis and illustration. A vessel taking on ballast-water in one global region, with its particular fauna and flora, and transporting and discharging it in another region thus leads to the transport of those alien, invasive or non-indigenous species (NIS) which have the potential to disturb the ecological balance at the receiving area (Olenin et al., 2011; David and Gollasch, 2008). As an ancillary vector of NIS, organisms can be transported on the hull, anchor and anchor chains. The various ten-tenets criteria would need to be formalised to provide guidance regarding what Response and Measures could be undertaken for prevention control as well as mitigation, recovery and compensation control. Our example formalisation for them is shown in Table 2 and we have provided subjective comments and an individual ranking for the ten criteria from 1 to 5, representing *not important at all* (score of 1) and *very important* (score of 5).

The completion of these elements in Table 2 provides a view of the State change on the natural system (S) in an ecosystem event that in turn generates Impacts on human Welfare (I(W)) and subsequent consequences. The importance of these then fits with the ultimate aim in marine management being to protect and maintain the natural functioning while delivering the ecosystem services and their resultant benefits required by society (Elliott, 2011). We consider most of these criteria as important to avoid the consequences selected, as well as any others not contemplated in this example. The ratings in the second column of Table 2 reflect our subjective assessment of the criteria that were defined in Table 1.

Table 2 – The Ten Tenets Applied to Ballast Water Discharges

Socially desirable/tolerable	Very important; score =5
Ecologically sustainable	Very important and easy to do; score = 5
Economically viable	Neutral but should not cost too much; score = 3
Technologically feasible	Important and should be easy to do; score = 4
Legally permissible	Important and should not be difficult to follow legislatively; score = 4
Administratively achievable	Important and should not be difficult to administer; score = 4
Politically expedient	Important and a vote winner; score = 4
Ethically defensible	Important and should not be difficult to justify; score = 4
Culturally inclusive	Not an issue; score = 1
Effectively communicable	Important and should not be difficult to communicate; score = 4

We next formulate our main ecosystem event process from a risk source related to water, i.e. a ship at sea or docked at a port development that is summarised in Figure 3. The highlighted boxes outline our specific example of ballast water discharge for consideration, which is especially relevant given that receiving ferry ports in the Baltic Sea region, e.g. Helsinki or Stockholm, show elevated levels of NIS (Olenin et al., 2011). Again, this manifests as an ecological change and the loss of ecosystem service and societal benefits.

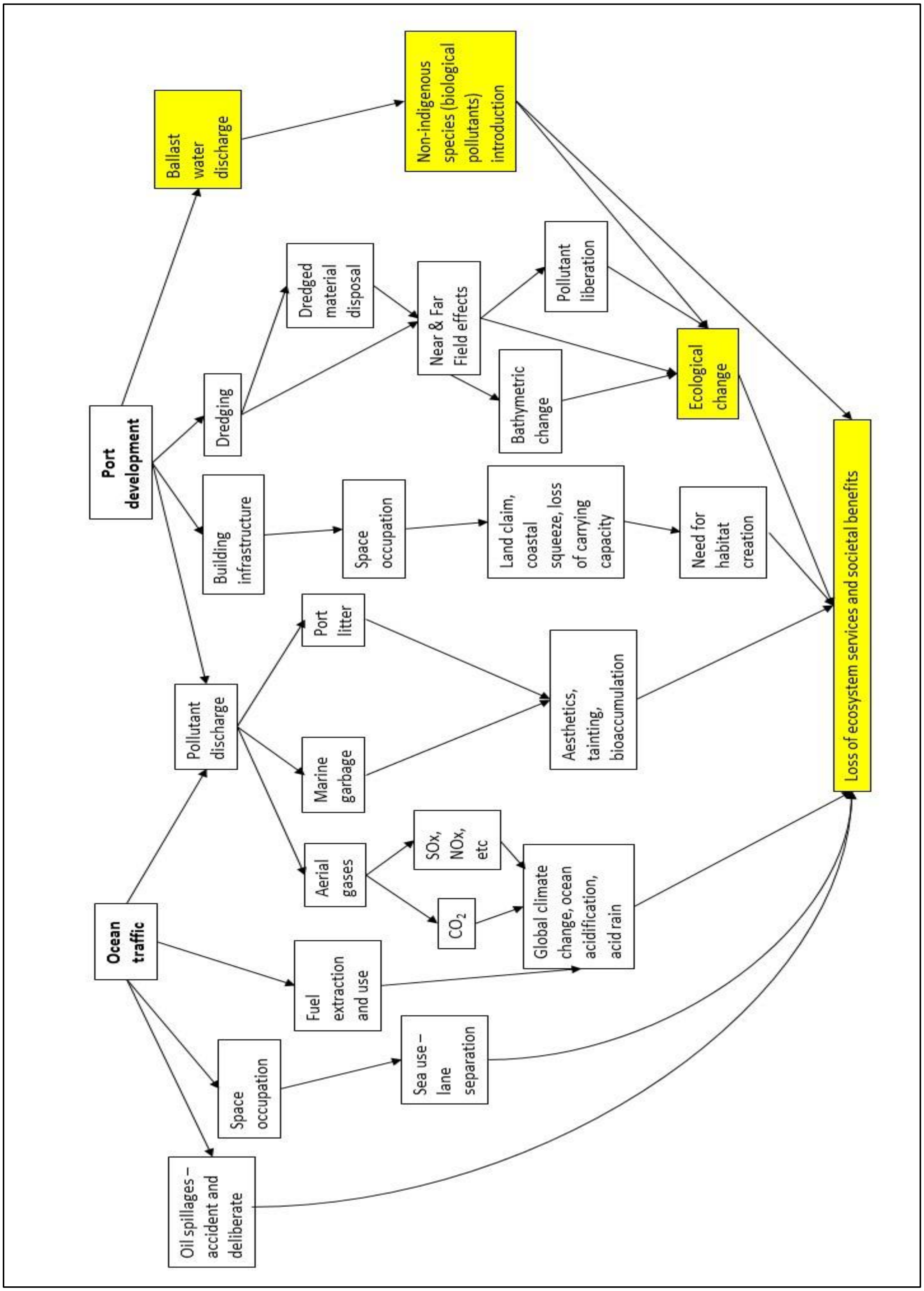

Figure 3 –Example model of ocean traffic and port development environmental effects including Bow-tie Analysis of ballast water discharge main ecosystem event (highlighted boxes)

The Response and Measures for prevention control on the causation side of the Bow-tie could include monitoring of discharges through all of a ship's discharge ports via effluent sensors during each port of call along its route. The monitoring would need legislative support but while monitoring is not a preventative measure *per se*, it is required to determine whether any control mechanism is effective. This will allow the authorities to know whether or not a ship has discharged any dirty ballast water, what the polluting components might be, and their percentage composition in the sample. Continuous monitoring would provide a baseline of what might be considered 'normal' as well as what might be excessive.

If such a prevention control analysis determined that two ships were responsible for the excessive discharges, then distinct mitigation, recovery and compensation controls could be applied as required. For example, mitigation could include preventing the two ships from sailing onward until their ballast water systems were repaired; it is axiomatic that with NIS entry from ballast water discharges it is not possible to eradicate the species in receiving marine waters once liberated (Olenin et al., 2011) and so the emphasis has to be placed on 'prevention rather than cure'. Ballast water exchange en route will partially control the introduction of NIS, as long as there are no 'stepping stones' for organisms to hop across shipping routes, and disinfection of ballast water through, for example, ozone treatment, would prevent NIS discharge either en route or at the receiving port.

We contend that the framework detailed here is merely a formalised and rigorous approach which summarises the risk assessment and risk management carried out daily by port and navigation managers. The strength of this framework comes from the interaction of many causes and many possible consequences for a particular ecosystem event. While limiting our overriding event of water pollution to one cause or event, ballast water discharges, it is necessary to consider the interactions among other potential causes or events occurring simultaneously, for example ballast water discharges, dredging, oil spillages and other pollutant discharges.

Hence, a major challenge in port and navigation management is to include the cumulative and in-combination effects of all activities within the shipping sector, between the shipping sector and other uses and users of the seas, and between those uses and users. Thus within this conceptual framework, the ten-tenets set the scene for what should be normative, proper activities while the DAPSI(W)R(M) approach allows for a systemic and holistic consideration of the causes and consequences using the principles of bow-tie analysis. As shown by Boyes and Elliott (2014, 2015), the control on marine activities and their repercussions requires an extensive legislative and administrative control which ranges from the international (e.g. the International Maritime Organisation), through the regional (e.g. in Europe the EU Directives such as the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive) to national legislation.

Conclusion

This paper has presented an integrative conceptual framework for balancing hard, quantitative environmental sciences and soft, qualitative management sciences. Our simple example illustrates the way that the framework can be used in practice by researchers, businesses, governments and other stakeholders. In doing so it makes a contribution and also brings together work in logistics and SCM and the estuarine sciences. However, this relatively new framework is the culmination of several concurrent but different strands of research primarily in marine sciences. Thus, there is a need to empirically test the framework in an-depth research studies to verify it veracity and robustness. Its success depends on the adequacy of our conceptual knowledge of the causes and consequences of human activities, our understanding of the structure and functioning of the marine system and our ability to quantify those interactions. It requires port and navigation managers to embrace the plethora of decisions affecting the environmental, economic, technical, societal and legal frameworks and hence will need greater training in these aspects. It also requires the environmental managers and regulators to understand the constraints of global port and shipping operations. With greater information and further data it will be possible to convert the framework described here to a decision support system aiming for real-time management of the activities and their consequences.

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