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Developing a conceptual influence diagram for socio-eco-technical systems analysis of biofouling management in shipping – A Baltic Sea case study

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ABSTRACT

Ship hulls create a vector for the transportation of harmful non-indigenous species (NIS) all over the world. To sustainably prevent NIS introductions, the joint consideration of environmental, economic and social aspects in the search of optimal biofouling management strategies is needed. This article presents a multi-perspective soft systems analysis of the biofouling management problem, based on an extensive literature review and expert knowledge collected in the Baltic Sea area during 2018–2020. The resulting conceptual influence diagram (CID) reveals the multidimensionality of the problem by visualizing the causal relations between the key elements and demonstrating the entanglement of social, ecological and technical aspects. Seen as a boundary object, we suggest the CID can support open dialogue and better risk communication among stakeholders by providing an illustrative and directly applicable starting point for the discussions. It also provides a basis for quantitative management optimization in the future.

1. Introduction

Shipping is a major pathway to non-indigenous species (NIS) introductions and hence a significant threat to ecosystems worldwide (Molnar et al., 2008; Olenina et al., 2010). For instance, in Europe, shipping contributes to, on average, over 40% of the new NIS introductions (Nunes et al., 2014). Due to marine traffic, the introductions are not only conditional on environmental and ecological constraints, but also the shipping network characteristics and the different types of vectors within the network (Banks et al., 2015). Ballast waters and ships' immersed hulls are the two most remarkable marine NIS vectors. The International Maritime Organization (IMO) has identified biofouling, a natural accumulation of organisms on surfaces, as one of the main economic and ecological concerns of the shipping (IMO, 2011), which highlights the need for uniform regulations concerning the ship immersed hull maintenance practices.

Biofouling is a disadvantage for shipping companies due to the friction of attached organisms causing losses in fuel, maneuverability, and maintenance (Schultz, 2007). The ship biofouling management, simply put, comprises practices of keeping the hull clean. Nowadays, ship biofouling management includes two main methods: coating and in-water cleaning (IWC). Compared with ballast water treatment, biofouling management is more beneficial to the shipping company as it results in both enhanced hydrodynamic performance and reduced fuel costs (IMO, 2014; Lindholdt et al., 2015). Simultaneously, less greenhouse gasses and air pollutants are emitted, and the risk of NIS introductions is inevitably lower. On the other hand, poor biofouling management and inefficient legislation may lead to increased risk at multiple ecological and economic levels (Fernandes et al., 2016; Morrisey et al., 2013; Scianni and Georgiades, 2019).

Biofouling is expected to have higher relative importance than ballast water on ship-mediated NIS introductions in many sea areas (e.g. North Sea (Gollasch, 2002); Arctic (Chan et al., 2016); NW Spain (Cuesta et al., 2016); Canada (Lacoursière-Roussel et al., 2016); and North-

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America as a whole (Ruiz et al., 2015). Despite the strong contribution and evidence of biofouling as a prominent vector, a regulatory policy similar to International Convention for the Control and Management of Ship's Ballast Water and Sediments (BWM Convention) (see IMO, 2004) is not yet available. Yet, regional approaches to address the topic such as IWC exist (see e.g. Krutwa et al., 2019). For instance, the EU has laid several legislative measures to prevent NIS spreading, including Marine Strategy Framework Directive (MSFD), Biodiversity Strategy, and Regulation on the prevention and management of NIS introductions (EU, 2014). Further, the Baltic Marine Environment Protection Commission (HELCOM), an advisory administrative body in the Baltic Sea area, is leading the development of a roadmap to regional biofouling management (BMEPC, 2019). National and local regulations have been laid in Australia, New Zealand, and California to control biosecurity (Department of Agriculture and Water Resources, 2018) and biofouling management, antifouling (AF) coating and IWC practices, of domestic and international ship arrivals (California Code of Regulations, 2017; Department of Agriculture, and Water Resources, 2019; Department of the Environment [DOE] and New Zealand Ministry for Primary Industries [MPI] (2015)). However, in general, the lack of systematic monitoring in ports and other dispersal hubs has been hindering the broader implementation of effective regulations (Lehtiniemi et al., 2015), partly due to the vessel and port -specific characteristics that impact the required inspection methods (Zabin et al., 2018).

Biofouling management is about balancing among economic, environmental and societal aspects (Fig. 1). The potential negative impacts of both NIS (Ojaveer and Kotta, 2015) and the management measures on the native organisms, toxic releases from biocidal AF coatings (Ytreberg et al., 2017; Lagerström et al., 2018), and degradation of the ecosystem services such as food provision, sea nourishment, water provision, and coastal habitats due to NIS introductions (Katsanevakis et al., 2014) should be acknowledged while planning the best practices. Consequently, information on species introductions and biofouling capabilities, ship type -specific biofouling characteristics as well as evaluation of different AF and IWC techniques are needed. In sum, biofouling management is a good example of a complex socio-eco-technical system with the various interdependent factors and overlapping concern of different parties with equal aims to decrease the biofouling but due to different reasons. Thus, managing biofouling in ships is a mutual interest promoting favorable outcome for all parties (Davidson et al., 2016).

In this paper, we analyze - through a conceptual (soft) systems analysis (e.g. Bennet and Chorley, 2016) - the biofouling management problem in the Baltic Sea, one of the most heavily trafficked sea areas in the world. Based on the information gathered from various sources, we provide a narrative description of the problem and construct a conceptual causal influence diagram (CID) to visualize the complex and multidisciplinary nature of the socio-eco-technical system that generates the ship biofouling -related NIS risk in the area. The CID integrates information about the key factors and causal dependencies of the system, providing a multi-sectoral big picture of the management problem. Stated by Carriger et al. (2018), CIDs can enhance the inclusivity of multiple viewpoints, improving inference and common understanding about the conditional aspects of various management problems, as well as the impact mechanisms of potential management interventions. In this paper, the CID is used as a tool for conceptual framing and causal structuring of a cross-disciplinary management problem. We suggest the structured systemic representation can in the future not only support discussions among the relevant actors of the field, but also be used as a platform for integrating heterogeneous multi-disciplinary data, to create a quantitative decision support model that could even further improve the evidence-based risk management capability of the society.

The paper is structured as follows. Section 2 first introduces the study area (the Baltic Sea), the collected data and the methods applied. In Section 3, the results of the system's analysis are presented, first in form of a narrative, which is then structured and visualized as a CID. The results and their societal relevance are discussed in Section 4.

2. Materials and methods

2.1. The Baltic Sea as a study area

The Baltic Sea (BS), located in Northern Europe and classified as a Particularly Sensitive Sea Area by IMO, is among the world's most polluted sea areas (see HELCOM, 2010) and one of the largest brackish water basins (Fig. 2). Due to low salinity and winter temperature, together with high seasonal and regional variation (Leppäranta and Myrberg, 2009) as well as remarkable anthropogenic pressures (Korpinen et al., 2012), the BS is a challenging living environment for organisms. Hence, most of its species are under constant stress, which makes the resilience of the ecosystem low (Tomczak et al., 2013). In addition, biodiversity is low resulting in a small number of keystone species and rather simple food web compositions (Karlsson and Eklund, 2004). Consequently, NIS-induced impacts on the habitats and food web dynamics may be decisive and harmful for the whole ecosystem (see Ojaveer and Kotta, 2015).

Ship traffic is intense in the BS: according to HELCOM (2018), the number of port visits was close to 300,000 in the year 2015. Almost half of these visits were made by passenger ships, mainly due to the high number of ferry connections between coastal towns and cities. The most common commercial ship types are cargo, tanker, passenger and container ships (HELCOM 2018), which account for 80% of the traffic of large IMO registered ships in the BS. The two most numerous ship types in the BS are cargo (48%) and tanker (22%). The characteristics of the BS shipping have a direct effect also on the NIS issue. Ships arriving outside of the BS exhibit a greater risk of new NIS compared with internal traffic ships that mainly contribute to the risk of secondary spreading (Ojaveer et al., 2017). Almost one third of the cargo ships are transporting to or from the BS increasing the primary NIS spreading in the BS. Generally, certain harbors are, due to the busy transportation, considered as hot spots for aquatic NIS (Ferrario et al., 2017; Wang et al., 2018). Moreover, ports that are busy and highly connected with the global shipping network, act as stepping-stones for NIS distribution (Floerl et al., 2009; Xu et al., 2014).

2.2. Data

To analyze and structure the management problem, we gathered data and information from the literature, stakeholders and experts (Table 1). The contribution of different data sources to the main themes relevant to the management system and the developed CID are presented under Section 3.

We gathered and reviewed scientific and grey literature to map the prevailing state of knowledge considering the biofouling management in general and in the BS area. The following key themes were recognized and further elaborated: (1) the biological perspective of the biofouling management such as NIS introduction risk and ecotoxicological issues, (2) different management methods (coating and IWC) with their limitations and utilities, (3) the special characters related to BS, (4) the ship traffic and ship related issues and finally, (5) recent biofouling management models.

The interview data was collected and analyzed in 2018–2019 through phone and face-to-face interviews. The interviewees included master mariners (n = 2), coxswains (n = 3), chief engineers (n = 4), and officers (n = 3), who represented shipping companies having RORO, ROPAX and tanker type fleets operating all over the BS. In addition, a representative of an IWC company operating in the BS was asked for further information via email. The purpose of the interviews was to achieve information about the prevailing biofouling management options and practices, the decision-making process, as well as the stakeholders' opinions and knowledge gaps considering biofouling management. The questionnaire used for the phone interviews is provided in Appendix I, for the face-to-face interview themes and the email discussion themes in Appendix II.

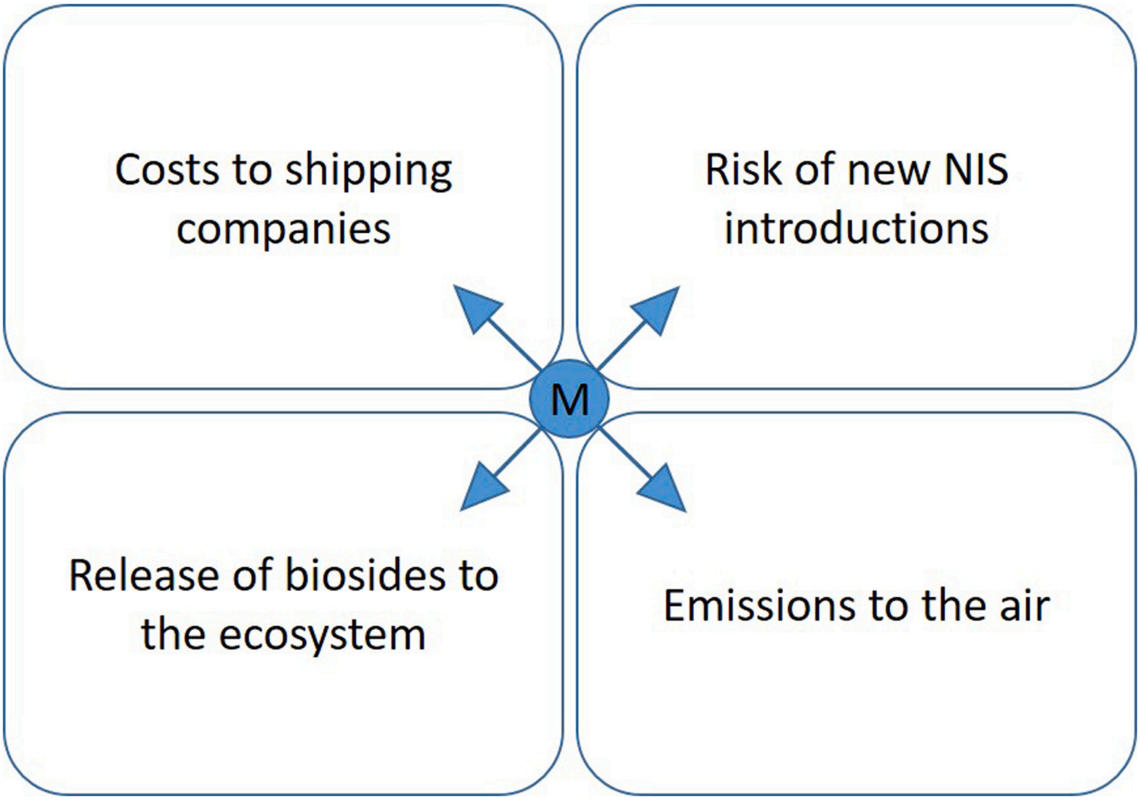

Fig. 1. The biofouling management (M) of ship is a balancing act among the four perspectives presented in the picture.

Expert workshops and meetings were held in 2018–2020 among a consortium of the project COMPLETE,[1] consisting of scientists, authorities and other specialists working actively with the NIS related topics in the BS area. The experts helped the authors to understand the complex biofouling management topic and the special features of the BS. The authors were the organizers and facilitators of two workshops and participants of the project meetings, observing but also participating in the discussions as project members to gain holistic multi-perspective understanding about the issue. The meetings involved open discussion between the experts and authors but the workshops had more limited themes. More information on the meetings and workshops is provided in Appendix III.

2.3. *Influence diagrams*

Influence diagrams (ID) are graphical causal models that represent the framing and structure of decision problems, mapping the interactions of the various elements of a decision setting. An ID consists of three types of nodes: (1) decision nodes (rectangular) that represent the decisions to be made; (2) utility nodes (also *value nodes*; diamond-shaped), representing the preferences of the decision-maker, i.e. the experienced utilities / losses against which the decisions are evaluated; and (3) chance nodes (oval-shaped) that are the intermediate nodes representing the system that connects the decisions with the utilities. The system consists of a set of interlinked factors that are somehow dependent on the decisions evaluated and further on, through some mechanism, impact the level of utilities or losses in focus.

Typically presented as the generalizations of Bayesian Networks, IDs are most often operated in the context of Bayesian decision analysis, where they enable quantitative analysis of complex decision problems (Jensen and Nielsen, 2007). When represented as a Bayesian Network, where the dependencies among the variables are formulated as conditional probability distributions, an ID can solve multi-criteria decision optimization problems under uncertainty. Such IDs can also be used to analyze the value of information of different factors, prior to decision-making (Mäntyniemi et al., 2009).

As suggested by Carriger et al. (2018), even qualitative influence diagrams that describe the conceptual influence relationship among the nodes, but do not include information about the strengths of influence, can support decision analysis. Through structuring and visualization, the approach can improve understanding about the conditional aspects of management problems and the impact mechanisms of the potential management interventions. The transparent systemic model can reveal to the decision-makers, what they are actually choosing between, when the decisions are made. Social-environmental management problems are typically highly complex by nature: either directly or indirectly they touch several sectors of the society in parallel. When questions are getting more complex, formal tools for integrate knowledge and support rational thinking are needed (Owie et al., 2017).

In this study, we developed a conceptual ID (CID) of the biofouling management problem, based on the data presented in Section 2.2. The CID was built in three steps: 1) Specifying the possible management actions 2) Defining the key risks and utilities connected to the biofouling and the management actions 3) Structuring the risk-generating eco-technical system as a causal network that represent the mechanisms linking the utilities / risks and the management actions.

The CID approach has been earlier applied in environmental management studies by e.g. Haapasaari et al. (2012), Parviainen et al. (2019) and LaMere et al. (2020) (see also Carriger and Parker, 2021). Examples of quantified ID models are presented e.g. in Helle et al. (2015), and Pihlajamäki et al. (2020). Few causal models considering the biofouling management in shipping have been developed. While assessing the economic and environmental effects of hull management of tankers

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[1] EU Interreg Baltic Sea Region -project “Completing management options in the Baltic Sea Region to reduce risk of invasive species introduction by shipping” https://balticcomplete.com/

Fig. 2. The Baltic Sea is located in Northern Europe and has nine coastal states.

Pagoropoulos et al. (2017) present a causal loop diagram of the hull management system. Wang et al. (2018) have developed a life cycle model for a short route ferry, suggesting an optimal hull fouling management strategy from the economic and environmental perspective, however disregarding the NIS introduction risk. Uzun et al. (2019) present a time-dependent predictive model on the biofouling growth to support the hull management scheduling.

The present CID takes the widest perspective so far, both in terms of the ship types, the biofouling management strategies, and the management evaluation criteria. Our analysis includes both the coating and IWC strategies as the optional management approaches, considering their effectiveness for different ship types. The model makes visible the complex system of divergent mechanisms through which these strategies affect the NIS introduction risk, ecotoxicological risk, carbon dioxide emissions and costs related to fuel consumption and biofouling management, given the key features of a ship and its operational profile.

3. Results

Based on the collected data and information, the biofouling management system and its main components are first presented in a narrative format. The themes and questions covered by each data form are presented in Table 2. Hereafter, the data sources are referred to using the abbreviations in Table 2. The management problem, formulated as a

Table 1
The timing and methods of data collection.

Data collection method	Time of collection
Face-to-face interviews	May–September 2018; March–October 2019
Literature review	2018–2019
Email discussion	October 2018 and November 2019
Phone interviews	Autumn 2019
Workshops	October 2018 (Helsinki, Finland); April 2020 (online)
Project meetings	April 2018 (Riga, Latvia); December 2018 (Gothenburg, Sweden); April 2019 (Klaipeda, Lithuania); December 2019 (Jurmala, Latvia)

Table 2
Contribution of the data sources to the main themes of the biofouling management problem.

Themes with respect to the management problem	Data source			
	Literature review	Expert meetings and workshops [EMW]	Interviews with shipping companies [SC]	Discussions with the diving company [DC]
General problem framing	X	X	X	X
Environmental impacts of NIS	X	X		
Biofouling process	X	X	X	X
NIS introduction probability	X	X		
Vessel-related technical aspects	X	X	X	
Management options	X	X	X	X
Current regulation and governance: prevailing agreements, rules and legislation	X	X	X	
Ecotoxicological aspects of hull coating	X	X	X	
Decision making practices in shipping companies		X	X	
Costs related to biofouling management	X		X	X

CID, is presented in Section 3.2.

3.1. Narrative

3.1.1. Biofouling as a biological process explaining the NIS introduction risk

Many marine sessile organisms live attached to an animate or inanimate surfaces. Specifically, biofouling means the accumulation of species on wetted, inanimate surfaces. Attachment is driven by physical and chemical stimuli, cues that are often species-specific. Physical cues, such as surface roughness, light and other environmental conditions, hydrodynamics, and substratum type determine physical attachment conditions for primary fouling organisms (Murthy et al., 2008). However, chemical cues are generally more important to the attachment process than physical ones, and they are often associated with other fouling organisms and biofilms (see the reviews of Hadfield and Paul, 2001; Fusetani, 2004; Lambert, 2005). Together with food availability, the physical and chemical cues also determine the growth conditions for different biofouling organisms (Uzun et al., 2019).

Hull coating and vessel speed together with environmental conditions, hydrodynamic forces and species assemblage determine the amount of biofouling, i.e. the biofouling level. The biofouling accumulation on a certain surface is a function of time: Biofilm begins to form promptly after the surface is exposed to water, and as described above, suitable primary fouling organisms are attracted by biofilm chemicals, while larger macrofoulers accumulate within a couple of weeks (Amara et al., 2018; Yebra et al., 2004). The organism's morphology, life history traits, and biochemical characteristics influence the attachment strength (Coutts et al., 2010a; Murray et al., 2012). Low surface-energy coatings, such as silicone, increase the dislodgement probability due to the low adhesion strength (Davidson et al., 2020; Holm et al., 2006) and thus, the biofouling level as well as the concomitant NIS introduction risk remains moderate. However, high biofouling level leads to high weight of the biofouling assemblage, which is subjected to increased hydrodynamic drag forces and hence, an increased dislodgement probability. This, in turn, leads to higher NIS introduction risk.

Species biodiversity and the length of growing and reproductive seasons vary between marine ecosystems. Consequently, ship operating latitudes have an explicit effect on propagule size (Sylvester et al., 2011), described as the number of individuals transferred by a ship (e.g. Lockwood et al., 2005). Thus, the biofouling level and NIS introduction risk differ spatially. The environmental conditions in the departure and destination ports as well as along the route may vary considerably and only some species translocate and survive. Accordingly, in the BS, the number of NIS varies between areas (Ojaveer et al., 2017). Although some species may have less severe impact or do not even have verifiable effects (Ojaveer and Kotta, 2015) in the new environment, some other NIS may replace the native species and change the fundamental processes of the whole ecosystem (Molnar et al., 2008). Therefore, all NIS introductions in the BS should be avoided (see HELCOM, 2018b).

3.1.2. Vessels and their operational profiles

An ideal hull is clean and smooth inducing minimal drag. All forms of physical roughness, such as cracks and crevices, as well as biofouling on a hull increase the hydrodynamic resistance on the hull surface (Lackenby, 1962). Depending on the species assemblage and biofouling level, the biofouling organisms can substantially increase the hull roughness and resistance (hydrodynamic forces), which results in increased fuel consumption and emissions (Schultz, 2007). Fouling that substantially increases drag friction forms in 1–2 weeks (Hunsucker et al., 2016) depending on the species assemblage and growth conditions (see Uzun et al., 2019). According to Schultz et al. (2011), even a slime layer can increase fuel consumption up to 10%.

Further, the ship type, the hull form as well as the main dimensions together with bow and stern structures determine the wetted surface area (WSA) of the ship. The WSA is immersed and hence a potential habitat for biofouling species. Specifically, the niche areas e.g. propeller thrusters, sea chests, and rudder stock (for detailed list see IMO (2011)) are preferred by fouling species due to the lower flow compared with a flat hull. Thus, the species abundance and number in niche areas can be manifold compared with the hull (see Davidson et al., 2016 and references therein). The share of niche areas varies between ship types (Moser et al., 2017).

The stakeholder interviews, expert meetings and workshops helped to understand the differences between various ships and operative profiles highlighting the case specificity of the biofouling management decisions [EMW; SC]. The ship's operational profile affects the nascent biofouling level and selected management procedures, consequently. The operational profile describes the characteristics of the ship's normal operation and can be described both in the short and long term, being determined by various factors such as:

- Cruising speed profile on the route
- Loading conditions and trim
- Geographical sea areas
- Time spent in the sea, ports and anchorage areas
- Engine loading conditions over the voyage

- Dry-docking interval (long-term factor)
- Other factors describing the operation of the ship. [EMW; SC]

Especially long idle periods in ports or anchorage areas increase the biofouling potential (Floerl and Coutts, 2009; Sylvester et al., 2011; Davidson et al., 2020). Correspondingly, the longer the organisms are attached to the hull, the higher is the risk of reproduction (Minchin and Gollasch, 2003), while the species-specific variation in propagule age and fitness affect the reproductive output (Schimanski et al., 2016, 2017). Often velocity above 4–5 knots restricts the settlement of biofouling species (Lindholdt et al., 2015), while dislodgement is species-specific (Coutts et al., 2010a, 2010b; Davidson et al., 2020; Murray et al., 2012). In addition, the biofouling level increases positively with the time since the last dry-dock, when new coating is applied (Sylvester et al., 2011).

3.1.3. Management measures to control biofouling

The coating and IWC are the main methods of control the biofouling level of the ship. All methods have their own strengths and weaknesses. The IWC and main coating types with their pros and cons are presented in Fig. 3.

Hull coating is the most common method for biofouling management. Currently applied, commercially available solutions are either based on three coating technologies (Blanco-Davis et al., 2014; Lindholdt et al., 2015): 1) Chemical, biocidal AF technology, i.e. soluble control depletion polymers (CDP) or self-polishing copolymers (SPC); 2) Hard, insoluble coatings [SC]; 3) Mechanical, non-biocidal fouling release (FR) technologies.

CDP and SPC paints contain a biocide, usually copper, in addition to some booster biocide, while hard paints include high molecular weight polymers, such as epoxy (Yebra et al., 2004). SPC paints are the main biocide AF paints on the market and they provide protection at lower velocities (Finnie, 2006; Lindholdt et al., 2015).

The problem of copper and booster biocides is that they are toxic to both the target and non-target species (Martins et al., 2017; Ytreberg et al., 2017) and thus cause an ecotoxicological risk to the marine ecosystem. The copper release rate from the paint layer increases with increasing salinity and temperature (and decreasing pH), while biofilm is suggested decreasing it (Valkirs et al., 2003). The toxicity of copper is dependent on the concentration of the labile, inorganic copper (Cu^{2+}) (Brooks and Waldock, 2009; Luoma and Rainbow, 2008). In general, high salinity and the amount of organic and inorganic ligands decrease toxicity due to formed complexes and the following sedimentation, while low salinity increases toxicity, as copper retains its labile form. Thus, the copper release rates from paints should be adjusted area-specifically in the salinity gradient BS (Lagerström et al., 2018) since a low copper content of coating is efficient enough at low salinity rates (Bighiu et al., 2017). Especially marinas and harbors may exhibit relatively high, ecologically harmful copper concentrations (Eklund et al., 2010). According to the experts, the use of non-biocidal coatings especially in the areas of high copper sediment concentration is important ([EMW]; Nendza, 2007; Turner, 2010).

According to the interviewees, in the BS, non-biocidal hard coatings in combination with IWC are used especially in cruise ships, RORO and ROPAX vessels [SC]. In addition, hard coatings are highly resistant to mechanical wear thus being suitable for operation on icy conditions [SC]. FR coatings are based on a material that reduces adhesion strength, hence being efficient only on ships having short port visits as they are inefficient during idle (Ciriminna et al., 2015). However, the interviewees reminded us that FR coatings are expensive to apply and remove and can only be used in ice-free water areas due to the vulnerability of the coating to physical damage [SC]. The coating lifetime (efficiency) varies between solutions, being longer for the FR coatings (Lindholdt et al., 2015).

Despite the progress in the coating technology, additional measures are typically needed in order to keep the hull clean. In-water cleaning (IWC) is a method where the biofouling material is removed from the hull by divers or robots (IMO, 2011). IWC processes can be divided into proactive and reactive treatments: The former aims to prevent biofouling level from exceeding soft, slime layer fouling, while the latter refers to a treatment, where macrofouling is present (Scianni and Georgiades, 2019). The NIS introduction risk increases in IWC without capture but in IWC with capture, cleaning material is collected and the material treated properly to lower the probability of NIS introductions and biocide releases (Morrisey et al., 2013; Tamburri et al., 2020). The niche areas, however, can be hard or even impossible to clean and are thus often treated with a biocidal coating.

Forces applied to remove the biofouling material should be adjusted according to biofouling level and coating (see Oliveira and Granhag, 2016 and references therein). For soft microfouling, consisting of algae, bacteria, as well as spores and sporelings, the required force is two to three orders of magnitude lower than for hard, macrofouling organisms,

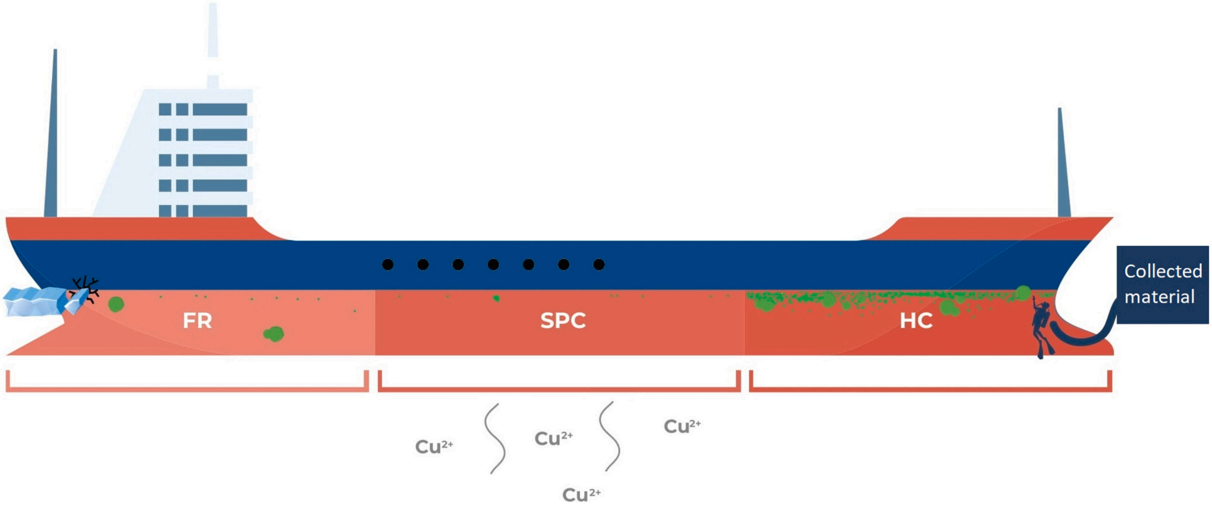

Fig. 3. The main coating types used in the BS are Fouling release (FR), Self-polishing (SPC) and Hard, non-biocidal coating. FR coatings can be used only in ice-free areas as the ice may break the coating, toxic copper is released from biocidal SPC coating and HC needs regular IWC. In reality, the hull coating is not managed sectionally with different coating types but one coating type is used for the whole hull. Niche areas, however, can be treated with a toxic coating type regardless how the rest of the hull is treated.

such as barnacles. Similarly, stronger forces are required to remove attached biofouling material from AF coating compared with FR coated surfaces (see Oliveira and Granhag, 2016).

Especially the reactive treatment shortens the coating service lifetime (Earley et al., 2014). However, depending on biofouling level, soft methods (such as grooming) can be used to clean the hull to reduce biofilm formation (Tribou and Swain, 2010; Hunsucker et al., 2018), without damaging the paint (Hearin et al., 2015; Tribou and Swain, 2017). Similarly, favorable outcomes for both AF and FR coatings have been achieved with water jets applied at appropriate time intervals and forces (Oliveira and Granhag, 2020). On the contrary, frequent cleaning interval during low fuel prices can lead the management costs outweighing fuel cost savings; however, emission savings will still occur (Pagoropoulos et al., 2017). Due to the inherent ecotoxicological risks involved in AF coatings and the lack of clarification regarding the best available technology (Scianni and Georgiades, 2019), IWC of such coatings may be prohibited (e.g. Department of the Environment [DOE] and New Zealand Ministry for Primary Industries [MPI], 2015).

Based on the interviews, IWC is rarely performed for the FR coating in the BS due to the rather low biofouling level [SC]. However, hard, non-biocidal coatings are cleaned monthly or bimonthly during the growing season [SC; DC]. The IWC and the procedures for collecting the released biofouling material affect the NIS introduction risk and vary in the BS as well as the regulations and monitoring concerning them

Fig. 4. The causal CID consisting of decision nodes (rectangles), chance nodes (blue ovals = technosphere factors; green ovals = ecosphere factors), utility nodes (orange diamonds = costs; purple diamonds = environmental impacts) and conditional dependencies (arrows) between them. When reading the CID, each arrow can be worded as “affect(s)”. A table explaining the meaning of each node is provided in Appendix IV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[EMW]. In addition, national occupational safety legislation and port provisions for underwater work set restrictions for diving activities especially in oil and chemical ports when tankers are being loaded [SC; DC]. Such regulations practically order IWC to be carried out in anchorage areas outside the ports, increasing the IWC costs for tankers.

3.2. Influence diagram

The systemic understanding developed in the study and described in the previous section, was the base for structuring the CID. The CID consists of six decision nodes (rectangles), 28 chance nodes (ovals), six utility nodes (diamonds) and 102 links (arrows representing conditional dependencies) between the nodes (Fig. 4). The decisions to be made by the ship operator are *IWC method (forces), IWC method (released material collection), IWC interval* and *Hull coating type* and *Hull coating renewal interval*. *Regulation* refers to the legislation that defines what the ship operator is allowed or required to do. The interests of the decision-makers and other stakeholders are represented by the utility nodes *Coating costs, Fuel costs, IWC costs*, *Emissions*, *NIS introduction risk* and *Ecotoxicological effects*. Appendix IV includes a table explaining the meaning of each node.

4. Discussion

We constructed a conceptual influence diagram, CID, that by synthesizing the prevailing knowledge (published literature complemented with expert-elicited information) and the perspectives and tacit knowledge of relevant actors, improves the holistic systemic understanding concerning the complex management problem of the ships' biofouling, specifically in the BS area. The CID is a graphical visualization of the issue, considering multi-disciplinary perspectives to the related risks and costs: (1) the risk of biofouling -driven NIS introductions, (2) the ecotoxicological risk due to biocidal antifouling paints, as well as (3) the increased fuel consumption of the ships due to hull fouling, and the consequent CO_2 emissions and (4) costs to shipping sector. The conceptual model makes transparent the mechanisms through which the existing biofouling management solutions affect the risk and cost levels.

The CID reveals the multidimensionality of the problem, demonstrating the entanglement of the social, ecological and technical aspects that should be recognized to reach sustainable biofouling management. To demonstrate this, in Fig. 4, we grouped the key factors of the model under the ecosphere and technosphere categories. This was not fully straightforward, however, as the line between ecological and technological is somewhat fuzzy (see Appendix IV). The ship's hull, for example, is a man-made physical object that on the other hand creates a substrate and a habitat for the living organisms. Thus, the hull actually is an interface node, belonging to the both spheres and binding them together. A stand of the fouling organisms, in turn, is a biological living entity that can disturb and unbalance indigenous communities and the local ecosystems. From the technical perspective, however, the stands are physical objects increasing the hydrodynamic resistance and further on the fuel consumption of the ship. Despite this, acknowledging their living nature is of utmost importance when the physical problem is controlled.

The gains and losses resulting from different biofouling management strategies are neither commensurable nor equally distributed; the management costs fall on the private sector, whereas the environmental risks caused by the operation have wider local, regional or even global societal consequences. Thus, biofouling management is a good example of a wicked problem (Rittel and Webber, 1973) that is hard to solve, lacking an univocally best solution and thus requires trade-offs between the environmental, social and economic well-being of divergent stakeholder groups. However, biofouling management is also a special case in a sense that under certain conditions the investments in risk management actions - if optimally selected and implemented - might bring some economic benefit for the shipping company by decreasing the fuel consumption while minimizing the negative environmental impacts. To specify the conditions under which this could happen, a quantitative optimization model is needed. We suggest that - if constructed applying the graphical Bayesian Network software - the presented conceptual ID could serve as a platform for integrating existing data (observational, experimental or modelled) (see e.g. Lehikoinen et al., 2015) and expert elicited probabilities (see e.g. Lehikoinen et al., 2013; O'Hagan et al., 2006), to create such optimization model.

As the CID shows, the hull coating type – the main instrument to regulate the biofouling level - affects the chemical and physical conditions of the substrate and further the biofouling level of the hull. In addition, copper release and ecotoxicological effects are dependent on the coating type and its copper content. The shipping route, on the other hand, affects the coating type since the FR coating, for instance, can be used only in ice-free areas - an issue that is relevant specifically in the Baltic Sea area. In addition, the CID proves that the main management actions: hull coating type and IWC, are interlinked. The suitable IWC method and interval depend on the coating type; HC requires regular cleaning, whereas the FR coating and SPC remain cleaner in the BS.

This analysis had its main focus on the management strategies of hull fouling, whereas the extent of niche areas was seen more as a factor increasing the NIS introduction risk, due to their limited controllability (variable “Niche areas” in the CID). The niche areas are often hard or even impossible to clean, thus it may be reasonable to use biocidal coating to keep them free from biofouling. However, when combined with the carefully planned proactive hull fouling strategy, the overall amount of toxic load is considerably lower in comparison with the situation, where the whole WSA is treated with a biocidal coating. In addition, the copper content of biocidal coatings should always be adjusted with the environment and be only as high as needed. Based on the recent studies, the release rate of copper with current biocidal coatings often exceeds the effective dose in brackish waters (Lagerström et al., 2020).

Relying on Carriger et al. (2018), we assume our CID can support the open dialogue and better risk communication between different parties by providing an illustrative and directly applicable starting point for the discussions. The CID can also be seen as a boundary object: concrete, often a visual object, being part of various social worlds and supporting the communication between them (van der Hoorn, 2020). Management of invasive species touches social values, risk perception, and institutional issues and hence, for effective risk communication, trust-building and strengthened participation between stakeholders and decision makers are required (Estévez et al., 2015). With the current information load, visuals provide a beneficial presentation compared with text or tabular formats (see van der Hoorn, 2020 and references therein). Finally, all parties can benefit from an easy-to-understand CID that supports sustainable and transparent communication and decision-making.

The developed CID is useful for anyone interested in biofouling management but especially for stakeholders such as the ship-owners. Working with system dynamic models has shown to improve the understanding about the system structure (Howick et al., 2006). Further, Carriger et al. (2018) suggest a CID can widen the perspective and decrease the errors and misunderstanding in human thinking. Based on the interviews, we noticed the crew and the technical staff of the shipping companies sometimes have a rather general, reductionist approach to biofouling issues. For instance, the concept of secondary spreading causing NIS risk inside the BS is not always realized and misunderstandings considering the toxicity of the current biocidal AF coatings exist. Traditionally, the biofouling management decisions are made based on the predicted savings in fuel consumption and maintenance costs (Schultz, 2004; Schultz et al., 2011), whereas the ship operators' better understanding about the optimal maintenance strategy could provide both economic and environmental benefits (Wang et al., 2018).

The interviewed shipping companies had a high priority for environmental issues and they were willing to use environment friendly management as long as it is economically sensible. According to the interviewees, the lack of information about the sustainability of different management options prevents them evaluating how sustainable their strategies actually are and whether they could improve their performance. Providing a structured visualization of the logic and mechanisms behind the sustainability-making (or alternatively, inhibiting) system, the developed CID has potential to increase the actors' awareness and understanding about the systemic and multi-sectoral nature of sustainability and, further on, their motivation towards more sustainable operation. The improved understanding is likely to promote the stakeholders' acceptance of current and future regulations, increasing their commitment and feel of justice (see Haapasaari et al., 2013).

The presented CID is the first biofouling management model of its kind. Considering economic and environmental perspectives to the evaluation and describing the impact paths of coating and IWC, it supports the comparison of these management methods, acknowledging the role of the ship types and their operational profiles. When it comes to earlier models, the economic aspect stays dominant, whereas the consideration of environmental aspects is fairly limited, covering often only one perspective, such as ecotoxicological risk or fuel emissions. The NIS introduction risk as the assessment endpoint is missing even in the latest models (see Wang et al., 2018; Uzun et al., 2019). Pagoropoulos et al. (2017) assessing the economic and environmental impacts of hull management schemes on the operation of tankers, discuss NIS and the challenges considering their environmental impact assessment. Based on the present analysis we state that due to their mutual dependency, the use of coatings and IWC should be planned together and thought as one biofouling management strategy. In addition, recognizing the multi-faceted socio-eco-technical nature of the management problem, the interdependency of economic and environmental risks and opportunities should be considered in the evaluation of the alternative strategies.

Although our CID is targeted specifically at the BS region in a sense that the interviewees represented companies operating in the area, the model provides a general reflection of the complex system of biofouling management in the marine environment. Thus, it can be utilized as a starting point, for exploring the biofouling management in other marine environments as well. The CID provides a systemic synthesis of the previously conducted (mostly globally representative) research in a visual format. In the future, augmented with quantitative information about the dependencies among the variables, the developed CID (or a simplification of it) can be developed into a decision support tool capable solving case-specifically optimal ship biofouling management options.

In the future, climate change and global warming can bring out new phenomena and challenges to the biofouling management. For instance, the decreasing share of ice-covered areas makes the FR coatings more widely applicable. However, the harbors can be full of ice floes preventing harbors' usage, and on the other hand, the work of scuba divers and robots performing the IWC. Therefore, the development of new coatings and IWC solutions are still needed (see Oliveira and Granhag, 2020). Finally, in a changing world an easy-to-update biofouling model, such as the CID is, can be highly useful.

CRediT authorship contribution statement

Emilia Luoma: Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing – review & editing. **Lauri Nevalainen:** Investigation, Methodology, Visualization, Writing - original draft, Writing – review & editing. **Elias Altarriba:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. **Inari Helle:** Conceptualization, Methodology, Validation, Writing – review & editing, Project administration. **Annukka Lehikoinen:** Conceptualization, Funding acquisition, Methodology, Validation, Visualization, Writing – review & editing, Project administration.

Declaration of competing interest

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

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Appendix I

Questions: The phone interviews

The phone interviews ($N = 3$) were performed for the officers of shipping companies ($n = 3$) operating in the BS. The contact information of the interviewees was received from the partners in cooperation with the project.

1. What kind of biofouling management methods you currently apply in your ship?
   a. Antifouling (biocidal)
   b. Fouling-release
   c. Something else, what?
   d. In-water cleaning
      - How often is the ship in-water cleaned (IWC)?
      - Where the IWC is performed?
      - Who makes the IWC decision and based on what criteria?
      - How is the IWC performed (by divers, robots)?
      - Will the removed material be collected?
      - How large part of the hull is cleaned?
      - How clean will the hull be (after cleaning)?
   e. Nothing, something else, what?
2. What is the approximate dry-docking interval of your ship?

3. What are the annual costs of the current biofouling management?
4. Considerations behind the choice of the current biofouling management method
   a. Would you be ready to change the biofouling management method you are using?
      - If yes, what could make you change the method?
      - If not, why not?
   b. How important you think the biofouling management is? Why?
   c. What problems do you see in using/choosing the biofouling management strategy for a ship? How would you solve the problems?
5. Do you think the biofouling management should be regulated?
   a. If so, how?
   b. If not, why not?

Appendix II

Themes: Face-to-face interviews

The face-to-face interviews ($N = 9$) were performed for the crew members (master mariners, ($n = 2$); coxswains (n = 3); chief engineers, ($n = 4$)) of RORO/ROPAX ships (n = 3) when one of the authors was conducting emission measurements and voyage data recordings on-board. The selection of the interviewees on-board was based on the interviewees' actual knowledge of the biofouling of immersed hull structures and the selected IWC practices. The interviews were conducted using a semi-structured method to gain access to the tacit knowledge of the field and to use a theme-based structure, giving the interviewees more freedom to highlight the current practices and experiences and what they see as important.

Introduction of the interview:

- Short presentation of the project and its goals to the interviewee
- The interviewee was asked to briefly describe his/her job on-board.
- The interviewee was asked to briefly tell about his/her experience in biofouling issues.

Anti-fouling strategy:

- Is biofouling noticed as a problem by the crew and if so, what kind of problem is it?
- What kind of anti-fouling strategy the ship (or the company) is following?
- What kind of hull coating treatment the immersed hull structures have (including different hull sections, product card of coating types)?
- How often the dry-docking is done (and when the last one was done)?
- Is there any estimation of the mechanical condition of the immersed hull structures and their surface treatments?
- Has the anti-fouling strategy been selected per single ship or does the whole shipping company apply one strategy with all the ships? Is the selected strategy workable?

In-water cleaning:

- Are in-water hull cleanings (IWC) performed on the ship(s)?
- What kind of IWC method is applied?
- What is the selected IWC frequency?
- How is the IWC frequency selected?
- Is there a noticeable difference in the rate of biofouling between the seasons (spring-summer-autumn)?

Experiences in operation:

- Is immersed hull biofouling noticeable when operating the vessel?
- If yes, how the observation can be done (e.g. noticed increase of fuel consumption, decelerated speed etc. - any concrete examples)?
- Do you have experiences from other shipping lines or ships?
- If yes, what kind of experiences/knowledge do you have?

Themes: the email interview

In addition, the following themes were discussed by email with a representative of one IWC company:

- Hull biofouling rate under different conditions (including seasonal effect)
- Type of biofouling in the Baltic Sea under different conditions (visually assessed by a scuba diver)
- IWC methods
- Typical durations of the IWC operations
- The costs of IWC for divergent ships
- Observed good practices and other practical experiences

Appendix III

The timing and location of the meetings and workshops with the COMPLETE project experts. The represented organizations: Kotka Maritime Research Association (KMRA, coordinator), Federal Maritime and Hydrographic Agency (BSH), Chalmers University of Technology (CHALMERS), Baltic Marine Environment Protection Commission – Helsinki Commission (HELCOM), Keep the Archipelago Tidy Association (KAT), Klaipėda

University (KU), Latvian Institute of Aquatic Ecology (LIAE), Finnish Environment Institute (SYKE), University of Gdansk (UG), University of Helsinki (UH), University of Tartu (UTARTU), South-Eastern Finland University of Applied Sciences (XAMK).

Activity	Themes	Represented organizations	Location and time
Project meeting	General (open discussion between participants)	BSH, Chalmers, HELCOM, KAT, KMRA, KU, LIAE, SYKE, UG, UH, UTARTU, XAMK	Riga in April 2018
Workshop I	the structure of the CID, biofouling management methods, spatial aspect, ship related issues, NIS introduction risk, ecotoxicological risk, costs, target group	BSH, Chalmers, HELCOM, KMRA, UH, XAMK	Helsinki in October 2018
Project meeting	General (open discussion between participants)	BSH, Chalmers, HELCOM, KAT, KMRA, KU, LIAE, SYKE, UG, UH, UTARTU, XAMK	Gothenburg in December 2018
Project meeting	General (open discussion between participants)	BSH, Chalmers, HELCOM, KAT, KMRA, KU, LIAE, SYKE, UG, UH, UTARTU, XAMK	Klaipeda in April 2019
Project meeting	General (open discussion between participants)	BSH, Chalmers, HELCOM, KAT, KMRA, KU, LIAE, SYKE, UG, UH, UTARTU, XAMK	Jurmala in December 2019
Workshop II	The final structure of the CID, IWC, hull coating, ecotoxicological risk, ship related issues, NIS introduction risk	BSH, Chalmers, HELCOM, KMRA, SYKE, UH, XAMK	(online) in April 2020

Appendix IV

The variable names, the description and the node type categories of the CID variables (Fig. 4). The asterisk (*) in the column Node type remarks that the authors experienced univocal categorization of the chance node challenging (and thus the factor the node represents could potentially be thought as an interface factor between the ecosphere and technosphere).

Variable name	Description	Node type (category)
Attachment of organisms	Whether the organisms can attach the hull (if yes, how firmly)	Chance (ecosphere)
Biofouling level	Amount of living organisms on the hull's surfaces and the height and hardness of the assemblage (soft vs. hard biofouling)	Chance (ecosphere)
Chemical conditions of the substrate (ship hull)	Chemical conditions on the ship hull affecting whether the organisms can attach or not.	Chance (technosphere)*
Coating costs	The costs of hull coating (depends on e.g. the coating type and the ship size)	Utility (costs)
Copper release to ecosystem	Rate of the copper release to the water from the biocidal coatings (depends e.g. on salinity, pH and temperature in the ecosystem)	Chance (technosphere)*
Cruising speed	The average cruising speed of the ship	Chance (technosphere)
Ecotoxicological effects	The toxic effects the copper loading has in the ecosystem	Utility (environmental impacts)
Emissions	The average amount of CO_2 released by the ship in a time unit	Utility (environmental impacts)
Fuel consumption	The amount of fuel the ship consumes in a time unit	Chance (technosphere)
Fuel costs	The fuel costs of the ship in a time unit	Utility (costs)
Fuel price	Fuel price per unit of volume	Chance (technosphere)
Fuel type	Whether the ship uses light or heavy fuel	Chance (technosphere)
Growth of organisms	How fast the organisms grow	Chance (ecosphere)
Hull coating type	The coating type used for hull coating (FR, HC or CDP, SPC)	Decision
Hull dimension	Dimensions of the ship's hull (e.g length, beam, displacement, draught)	Chance (technosphere)
Hull form	The shape of the ship's hull	Chance (technosphere)
Hull coating renewal interval	Time interval between the ship's dry-dockings, during which the coating is renewed (typically varies between 3 and 7 years).	Decision
Hull structures	The actual structure of the hull	Chance (technosphere)
Hydrodynamic forces (organisms)	The friction caused by the organisms attached to the ship hull	Chance (technosphere)*
Hydrodynamic resistance (ship)	The hydrodynamic resistance of the ship. Poor hull condition, biofouling level and speed increase the friction of the whole ship.	Chance (technosphere)
Idle time	The time share the ship spends in anchor/port (in a given time unit)	Chance (technosphere)
IWC costs	The IWC costs to the shipping company (depend e.g. on the ship type, size, method used and the IWC interval)	Utility (costs)
IWC interval	The time between two IWCs. In the Baltic Sea, during the growth season, the IWC is typically performed once-twice in a month.	Decision
IWC method (forces)	Whether The IWC method used is soft or hard. Soft methods (e.g. grooming) can be used for soft biofouling but hard methods (e.g. steel brushes) are needed for hard biofouling. The longer the IWC interval, the harder the assemblage of organisms is.	Decision
IWC method (released material collection)	Whether the organic debris released by the IWC is collected or not	Decision
Natural environmental conditions	The environmental conditions in the sea ecosystem (e.g. temperature, salinity, pH)	Chance (ecosphere)
Niche areas	The areas in the ship favorable for the species' attachment due to weaker flow and currents	Chance (technosphere)
NIS introductions	The actual amount of non-indigenous species introduced to a new area	Utility (environmental impacts)
Operation hours	The average amount of hours the ship operates in a time unit (inverse to the Idle time)	Chance (technosphere)
Potential of NIS introductions	The potential amount of non-indigenous species introduced to a new area	Chance (ecosphere)
Physical conditions of the substrate (ship hull)	The condition (smoothness vs. roughness) of the ships hull that serves as a potential substrate for the biofouling organisms to attach. Cracks and crevices makes the attachment easier compared to a smooth hull.	Chance (technosphere)*
Regulation	International and national regulation concerning what the ship owners are allowed or required to do when it comes to biofouling management of their ships.	Decision

(*continued on next page*)

(*continued*)

Variable name	Description	Node type (category)
Sediment copper concentration	The prevailing copper concentration in the sediment of an area in focus	Chance (ecosphere)
Ship size	The size class of the ship	Chance (technosphere)
Ship type	Type class of the ship, e.g. tanker, cargo, container, passenger	Chance (technosphere)
Shipping route	The route operated by the ship (defines e.g. the environmental conditions and the background sediment copper concentrations in the ports of departure and arrival and between them)	Chance (technosphere)
Species assemblage	The quality and quantity of different species in the assemblage of the attached organisms.	Chance (ecosphere)
Time of the year	The prevailing season (defines e.g. the likely temperature, ice and weather conditions along the ship's route)	Chance (ecosphere)
Total biofouling mass/ship	The biomass of all living organisms attached to the ship	Chance (ecosphere)
Wetted surface area	The surface area of the immersed ship hull	Chance (technosphere)

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