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A multi-criteria decision analysis model for ship biofouling management in the Baltic Sea

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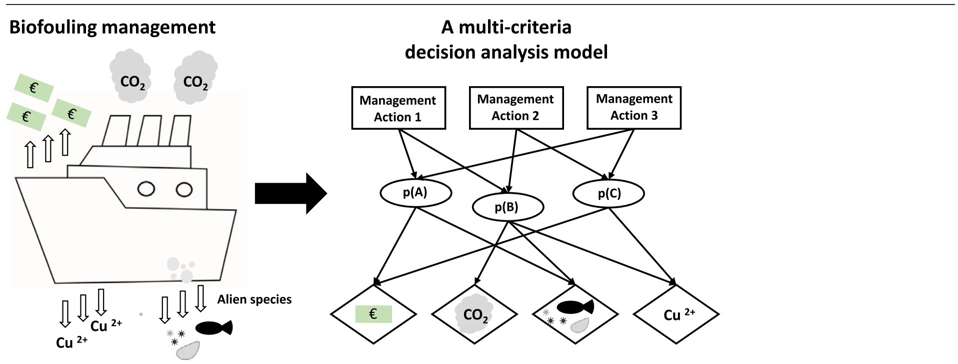
HIGHLIGHTS

- A multi-criteria decision analysis model to compare biofouling management strategies.
- Several environmental and economic aspects considered jointly.
- The first Bayesian network application in the field of ship biofouling management.
- Increasing holistic understanding can support the harmonization of the regulation.
- Biocidal-free coating with a regular in-water cleaning is a promising alternative.

GRAPHICAL ABSTRACT



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ABSTRACT

Biofouling of ship hulls form a vector for the introduction of non-indigenous organisms worldwide. Through increasing friction, the organisms attached to ships' hulls increase the fuel consumption, leading to both higher fuel costs and air emissions. At the same time, ship biofouling management causes both ecological risks and monetary costs. All these aspects should be considered case-specifically in the search of sustainable management strategies. Applying Bayesian networks, we developed a multi-criteria decision analysis model to compare biofouling management strategies in the Baltic Sea, given the characteristics of a ship, its operating profile and operational environment, considering the comprehensive environmental impact and the monetary costs. The model is demonstrated for three scenarios (SC1-3) and sub-scenarios (A-C), comparing the alternative biofouling management strategies in relation to NIS (non-indigenous species) introduction risk, eco-toxicological risk due to biocidal coating, carbon dioxide emissions and costs related to fuel consumption, in-water cleaning and hull coating. The scenarios demonstrate that by the careful consideration of the hull fouling management strategy, both money and environment can be saved.

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We suggest biocidal-free coating with a regular in-water cleaning using a capture system is generally the lowest-risk option. The best biocidal-free coating type and the optimal in-water cleaning interval should be evaluated case-specifically, though. In some cases, however, biocidal coating remains a justifiable option.

1. Introduction

The International Maritime Organization (IMO) recognizes biofouling, the accumulation of organisms on surfaces such as the ship hull (Amara et al., 2018), as one of the main concerns of shipping. Biofouling causes both economic (Pagoropoulos et al., 2017) and environmental (Ojaveer et al., 2017) risks: increased fuel consumption and emissions, and a pathway for the spreading of non-indigenous species (NIS) (Luoma et al., 2021a). NIS introductions create a major threat to marine ecosystems worldwide (Molnar et al., 2008). As management methods, shipping companies use hull coatings and in-water cleaning (IWC) (Schultz, 2007). However, biocidal coatings cause eco-toxicological load in the marine environment (Lagerström et al., 2018; Ytreberg et al., 2017), whereas the applicability of IWC or biocidal-free coatings are sometimes limited due to the operating environment (e.g. partial ice coverage hindering the use of fouling-release coating), or legislation (Scianni and Georgiades, 2019). In the Baltic Sea, the environmental characteristics, low salinity, partial ice cover during winter, and dense ship traffic increasing the NIS introduction risk, create extra challenges and thus biofouling management methods suitable for other marine environments cannot be transcribed directly to the area (Leppäranta and Myrberg, 2009).

Although the risks considering biofouling are well acknowledged, international legislation is still missing and only optional guidelines for biofouling management exist (International Maritime Organization IMO, 2011). There is an urgent need to support the shipowners in 1) choosing the optimal biofouling management strategy, 2) preventing further introductions of NIS, and 3) reducing toxic load to the marine environment (Ojaveer and Kotta, 2015). Methods enabling a holistic assessment of the system can support efficient management decisions and even the future enactment of legislation (HELCOM, 2010; Johnson and Andersson, 2016).

To meet this demand, we apply a Bayesian Network (BN) (Nielsen and Jensen, 2007) to integrate available data and knowledge, and to develop a multi-criteria decision analysis model (MCDAM) for probabilistic comparison of alternative biofouling management strategies in the Baltic Sea (a preliminary version being published in a preprint by Luoma et al. (2021b)). Primarily targeted to shipowners, the model can serve as an interactive decision support tool for ship- and route-specific comparisons. On the other hand, it also provides general information concerning the positive and negative aspects of divergent management strategies under various conditions, which makes it a potentially useful tool also for the regional maritime and environmental authorities and decision-makers.

A few causal models considering the hull biofouling management already exist. Pagoropoulos et al. (2017) presented a causal diagram of the hull management system, assessing the economic and environmental effects of biofouling management of tankers. Wang et al. (2018) built a lifecycle model studying the optimal hull fouling management strategy from the economic and environmental perspective. Uzun et al. (2019) developed a predictive model on the biofouling growth to support the timing of the management actions. Luoma et al. (2021a) developed a conceptual influence diagram (CID) to analyze the biofouling management problem multi-dimensionally in the Baltic Sea. Oliveira et al. (2022) built a tool enabling the shipping industry to make evidence-based decisions on hull maintenance strategies. The tool considers emissions, economic costs and health- and environmental damage costs. However, it does not consider the risk of non-indigenous species introductions. In addition, Murray et al. (2013) used boats' antifouling practices and traveling history to predict whether the boats are clean or fouled and Kacimi et al. (2021) modeled the likelihood of introduction and invasion of NIS in a certain port.

Compared to the earlier models, excluding the CID (Luoma et al., 2021a) that served as a basis for the present work, our MCDAM takes a wider perspective by considering different ship types, management strategies and criteria to evaluate their consequences. It is the first quantitative model considering several environmental and economic aspects: NIS introduction risk, eco-toxicological risk originating from biocidal coating, carbon dioxide emissions resulting from fuel consumption of the ship (linked to the level of biofouling), and costs related to fuel consumption and biofouling management, IWC and coating. In addition, the present MCDAM is the first BN application in the field of ship biofouling management. To demonstrate the developed approach, we compare alternative biofouling management strategies for three case-scenarios with different ship types and operating routes.

Since the publication of the preprint document (Luoma et al., 2021b), the MCDAM has undergone changes in some variable names and parameters. In the preprint, the focus was in introducing the MCDAM idea and structure and shortly discussing the potential use of it. In the current paper, we present the final MCDAM and apply it for actual management analysis based on nine scenarios (three cases with three operative and managements options for each). The discussion section focuses on the outcome of the analysis and the evaluation of the developed model. Thus, the majority of the present paper is original. The most notable similarities with the preprint are in the description of data and model variables, now included in the support materials. However, these are also described in more detail in the present paper.

2. Materials and methods

2.1. Study area

The Baltic Sea (BS) is a unique brackish water basin located in Northern Europe. Shallowness, low salinity and partial ice cover during winter, together with intensive marine traffic, make the BS a challenging environment for the organisms, lowering the resilience of the ecosystem (Tomczak et al., 2013). Further, these special characteristics affect the applicability of some biofouling management methods in the BS (Korpinen et al., 2012). Biocidal-free fouling-release coatings (FR) are not ice resistant and therefore can only be used in ice-free areas. In addition, the low salinity of the BS makes it particularly sensitive to biocides, such as copper and zinc, used in the biocidal coatings (BC). Generally, the copper release of coating increases with increasing salinity (Sanchez and Yebra, 2009; Valkirs et al., 2003). However, low salinity can increase the toxicity of copper (see Nasir, 2014; Ragnvaldsson et al., 2022). Finally, the busy marine traffic from outside of the BS causes a risk of new NIS introductions, while the internal traffic adds the risk of secondary spread (Ojaveer et al., 2017).

We divided the BS for modelling purposes into five sub-areas (Fig. 1). The division follows the ICES (International Council for the Exploration of the Sea) subdivisions (Fig. 1) but based on discussion with NIS experts, some of the areas were combined following the grades of salinity, water temperature and the number of reported NIS (section S3). In addition, the eastern part of the North Sea is included, since a major share of the marine NIS introductions to the BS originate from the area (Ojaveer et al., 2017).

2.2. Bayesian networks

BNs are probabilistic models for causal reasoning under uncertainty and have been used widely in environmental management studies (Fahd et al., 2019; Helle et al., 2015; Lecklin et al., 2011; Lehikoinen et al., 2013; Lu et al., 2019; Pihlajamäki et al., 2020; Rahikainen et al., 2014; Uusitalo,

Fig. 1. The study area division applied in the MCDAM, the North Sea and BS that is further divided to five sub-areas following the boundaries and numbering of the ICES subdivisions. 21–24: The southwestern Baltic; 25–29: The Baltic Proper; 28.1: The Gulf of Riga; 30–31: The Gulf of Bothnia; and 32: The Gulf of Finland. The stars indicate the ports selected for the scenarios analyzed in this article. Reprinted in part with permission from *arXiv preprint arXiv:2107.06810* (Luoma et al., 2021b). Copyright [2021] [arXiv].

2007; Uusitalo et al., 2012). For decision analytic purposes, a BN can be augmented with intervention variables (decisions), each variable having alternative states, to control the system, and utility functions (decision-making criteria) to define the preferred status of it. With such *Influence Diagrams*, the utility of certain decisions or series of decisions can be examined. BNs represent complex problems graphically, making them easier to understand (Klemola et al., 2009). This is a particular advantage when cooperating with stakeholders: a visualized model is relatively easy to explain and comprise, which is important to ensure goal-oriented cooperation (LaMere et al., 2020; Luoma et al., 2021a; Parviainen et al., 2019). For basic reading about BNs, we recommend e.g. the textbooks by Jensen (2009), Korb and Nicholson (2011) and Fenton and Neil (2013).

2.3. Data

The MCDAM compiles data from different sources. We 1) interviewed representatives of shipping companies ($N = 12$) and an IWC company to achieve information about the prevailing biofouling management options and practices (Luoma et al., 2021a; Luoma et al., 2021c); 2) conducted a literature review considering the biofouling management in general and at the BS (Luoma et al., 2021a; Luoma et al., 2021b); 3) performed seven on-board emission monitoring periods on three different ships, and recorded voyage data on five vessels (section S2: Tables S1–5); 4) retrieved data from the AquaNIS database[1] concerning the current NIS occurrences in different parts of the BS; and 5) utilized data on the prevailing copper concentrations in the BS sediments, found from the literature (Gubelit et al., 2016; ICES Metadata Catalogue, 2022; Nikulina et al., 2008; Vallius, 2012). In addition, two workshops and four project meetings were held with the COMPLETE project (www.balticcomplete.com/) experts consisting of scientists, authorities and other specialists working actively with the NIS related topics in the BS area.

The general principle of the MCDAM is explained under the Section 2.4 of the article. The detailed technical information concerning the MCDAM is

[1] http://www.corpi.ku.lt/databases/index.php/aquanis/.

provided in the support material as follows: Section S1 - The sources and utilization of data; Section S2 - On-board measurements and voyage data; Section S3 - A code for estimating the probability of new NIS introductions on a route; Section S4 - Definition of the NIS introduction risk value; Section S5 - Key assumptions of the MCDAM; Section S6 - Variable descriptions; Section S7 - Uncertainty associated with the expected utilities. In addition, the abbreviations used in the text are provided in Section S8 - The abbreviations. The model code and file are provided at https://github.com/mirkal-p/Biofouling_MCDAM.

2.4. Model structure and logic

As a starting point to construct the MCDAM, we applied the qualitative conceptual influence diagram (CID) developed by Luoma et al. (2021a) for structurizing and visualizing the biofouling management problem in the BS. We applied the CID to recognize the relevant information needed to solve the management problem, i.e. to answer what kind of management strategy would be optimal, given the characteristics of a ship, its operating profile and operational environment, considering the comprehensive environmental impact and economic costs.

The present quantitative model is a result from the collaboration and discussions of the multidisciplinary authoring team and the stakeholders representing shipping companies. The selection of the variables to be included in the quantified model was based on their relevance in terms of the intended end-use of the model as a decision support tool. We included such variables, which were relevant to study or that should be *instantiated* (i.e., set to a known state) by the end-user.

The MCDAM (Fig. 2) was constructed using Hugin Researcher software (version 8.8, Madsen et al., 2005). The MCDAM consists of 11 decision variables, 14 (probabilistic) random variables, 9 utility variables and the conditional dependencies (51 links) between them. The end-user is intended to instantiate all or part of the decision variables, affecting the state of the different random variables and finally to the gains and losses defined in the utility variables. Some decision variables do not represent actual management decisions, but are used as "*setting variables*", to provide case-specific information, when the analysis is conducted for a specific ship and/or route (the red and green rectangles in Fig. 2). If a decision node is not instantiated, its states have equal weights, representing the situation where the decision is not yet made or - concerning the setting nodes – where the user does not have (or want to specify) the information concerning the case.

The decision nodes can be instantiated or not but the more are uninstantiated the harder it is to interpret the results. The decision nodes are: *Ship type* (bulker, tanker, cargo, container, passenger, RoRo), *Time since coating* (numbered distribution), *In-water cleaning method (in the past)* (soft, hard),*Theoretical fuel consumption* (interval distribution 1000–5000 kg/h), *Fuel type* (light, heavy), *Coating type* (biocidal-free hard coating (HC), BC, FR), *In water cleaning (IWC) times/growing season* i.e. from April to end of September (0, 2, 6, 12), *In water cleaning and collection in the destination port* (IWC without a capture system, IWC with a capture system, no IWC), *Off hire costs* (none, 1 day, 2 days), *Annual shipping hours* (interval distribution 1000–8750) and *Routes* (ten different routes between the areas in Fig. 1; see Table S9).

Each route has two possible directions. This way the end-user can study whether the gains and losses related to the biofouling management differ depending on the direction. The direction affects especially the NIS introduction risk due to the areal differences in salinity and the species-specific tolerances (see sections S3–4). The sediment ecotoxicological risk depends on the direction (in case of the BC) because of the assumption the IWC always happens in the arrival port (see section S5). The background copper concentration in sediments differs spatially, and IWC increases the copper release (Brooks and Waldock, 2009; Eklund et al., 2010). IWC also increases the risk of NIS release, especially if a debris capture system is not used. These aspects could be considered when choosing the IWC site for a ship.

Besides the decision variables, the random variable *Wetted surface area (WSA)* can be set after instantiation of the setting variable *Ship type*. This specification allows one to provide more specific information about the size of the ship, as well as the area exposed to the biofouling and in the need of the coating and/or IWC. However, if this node is not instantiated, its distribution corresponds to the size (i.e. the corresponding WSA)

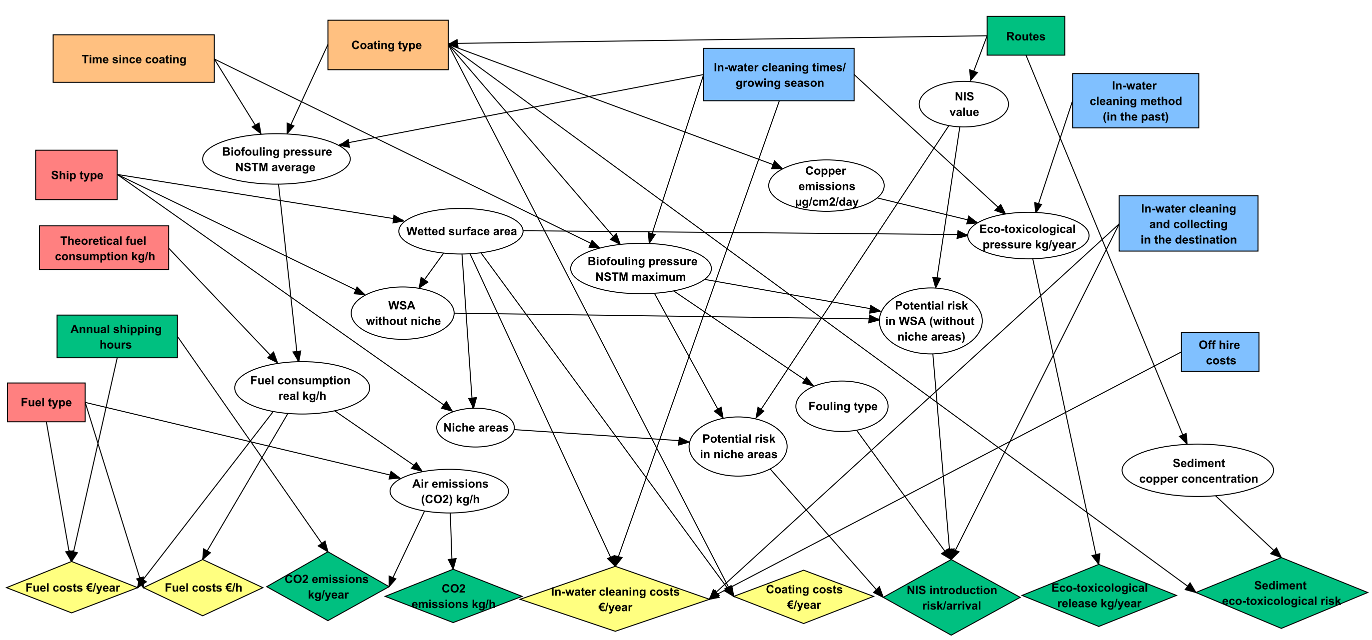

Fig. 2. Graphical representation of the MCDAM, with *decision variables* defining the alternative decision options to be analyzed (orange rectangles = coating-related; blue rectangles = in-water cleaning -related) and the case specific settings, if the analysis is conducted for a specific ship or ship type (red rectangles = ship-related; green rectangles = operational profile -related;), probabilistic *random variables* (white ovals) having alternative discrete states, the mutual materialization probabilities (given the state(s) of their parent variable(s)) being defined in conditional probability tables, *utility variables* defining the utility or loss, given the state(s) of the parent variable (s) (yellow diamonds = costs; green diamonds = environmental impacts) and the modeled conditional dependencies (arrows) between the variables. Reprinted in part with permission from *arXiv preprint arXiv:2107.06810* (Luoma et al., 2021b). Copyright [2021] [arXiv]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distribution of the selected ship type's fleet operating in the BS area (data from Polish seaports in 2018). Not instantiating this node might be of interest e.g. for the authorities interested in analyzing the general situation on a route, given the ship type.

The utility nodes, against which the management options are analyzed, are *Fuel costs* (€/year and €/hour); *IWC costs* (€/year); *Coating costs* (€/year); *CO_2 emissions* (kg/year and kg/hour); *Ecotoxicological release* (kg copper/year); *NIS introduction risk/arrival* (index); *Sediment eco-toxicological risk* (index). All the variables and utility functions are described in detail in the support materials, section S6.

Using the MCDAM, the end-user can study through the utility nodes, how the environmental impacts (CO_2 emissions, ecotoxicological release, NIS introduction risk and sediment ecotoxicological risk), together with the biofouling management and operating costs (fuel, coating and IWC costs) in each case (with a certain ship type and size, theoretical fuel consumption, fuel type and ports of departure and arrival) change, given the alternative coating types, IWC intervals, IWC methods and off-hire costs. Basically, almost all kinds of the decision and setting combinations are possible when creating the scenario to be analyzed. Only the use of FR is limited to the ice-free southern BS routes (1, 8 and 10, Table S9).

As the units of the utility variables are not mutually commensurable, the present MCDAM is not suitable for computational optimization. However, the gains and losses related to costs (biofouling management and fuel) and risks (NIS introduction risk, sediment ecotoxicological risk, ecotoxicological release and CO_2 emissions) can be compared between different scenarios and management strategies. Variable details, together with the logic and key assumptions of the MCDAM are presented in sections S5 and S6.

2.5. Scenarios

To demonstrate the developed MCDAM, and to compare the costs and effectiveness of the alternative biofouling management strategies, we present three case scenarios with three sub-scenarios for each. The first two cases are typical for the BS, the third represents a "bad case scenario" (Table 1). The case scenarios represent different types of ships on different routes, being thus not mutually comparable in terms of the biofouling management strategies. Their purpose is to give a picture of the variability and case-specificity of the risks, costs and utilities in general. However, each case scenario has sub-scenarios (A-C), and between these scenarios the comparison is meaningful. All the scenarios are built so that they are realistic, although it would hinder the full comparability. For example, the number of IWC per season is lower for BC than for HC, because in real life there is no need to clean the BC as often as the HC.

Scenario 1 (SC1A-C), with a passenger ship, is common in the Gulf of Finland where a busy passenger ship line between Helsinki and Tallinn crosses the gulf. Many passenger ships use non-biocidal HC and perform IWC regularly (scenario SC1A and SC1C). On the other hand, passenger ships using BC with IWC exist in the BS as well (SC1B). The IWC, however, is performed less frequently with BC than with HC. According to the interviews, the majority of the ships are still in-water cleaned without a capture system in the BS. The SC1C is otherwise identical with the SC1A but presents the results if the debris capture system (devices including collection and filtration) is not used. This MCDAM takes the viewpoint that all NIS introductions should be avoided (HELCOM, 2007) and thus all the NIS that have been found in the subarea were taken into account even if the ship line goes only inside one subarea.

Scenario 2 (SC2A-C) represents tankers coming from the North Sea and sailing through the whole BS. Tankers are often unable to perform IWC in the loading ports and thus are sometimes forced to pay off-hire costs when the cleanings occur. The SC2A and SC2B compare the results of two different coatings and IWC methods. The SC2A and SC2C are otherwise identical but the SC2C has IWC without a capture system like the SC1C.

Scenario 3 (SC3A-C) is an extreme case where a general cargo ship uses heavy fuel, has high shipping hours and fuel consumption. In SC3A-B, the BC with IWC without a capture system is used. The coating is aged, whereby despite the biocides, biofouling level is high. The infrequent cleanings and uneven surface allow hard-shelled organisms to attach firmly. Thus steel brushes must be applied for cleaning, increasing the copper load to the water. The SC3A is identical with the SC3B but the route is opposite. In SC3C the FR is used. Due to the ice conditions in the northern BS, southern BS is the only area where non-ice-resistant FR can be used at the moment. According to the interviews, the FR maintains the biofouling level low in the BS and thus IWC is needed more seldom or not at all. Here it is assumed that no IWC is performed.

3. Results

The scenario-specific expected values for the different utility variables are presented in Table 2. There are no remarkable differences in the expected fuel costs or CO_2 emissions when HC and frequent IWC (SC1A; SC1C; SC2A; SC2C) vs. BC and less frequent IWC (SC1B; SC2B) are applied. In SC1, the expected fuel costs with the former option are 0.9 % (72,000 €/year) lower and in SC2 1.9 % (26,600 €/year) higher, when compared to the latter option. In SC3 the expected fuel costs are 2.5 % lower (approx. 352,000 €/year) in SC3C with FR than in SC3A —B with BC and two IWCs.

The total expected IWC and coating costs are the lowest in the scenarios SC1B; SC2B; SC3C, where only a few or no IWC occurs, and the coating is BC or FR (Table 2). BC is cheaper to apply than HC and due to the toxicity of BC, fewer IWCs are needed. In SC1C, the IWC capture system is not used, lowering the IWC costs by 33 % (21,600 €/year) (despite the same number of IWCs) compared to SC1A. The same can be seen in SC2C: with six (6) IWCs, the IWC costs are 13 % (27,000 €/year) lower (despite the

Table 1
States of the decision and setting variables in the analyzed scenarios. HKI = Helsinki; TLL = Tallinn; RTM = Rotterdam; SVIK = Sköldvik; TBORG = Trelleborg (see Fig. 1), Pger = Passenger; Gcargo = General cargo, HC = hard coating; BC = biocidal coating; FR = fouling-release coating, IWC + c = In water cleaning with a capture system; IWC + no = In water cleaning without a capture system; no IWC = In water cleaning is not performed.

	SC1A	SC1B	SC1C	SC2A	SC2B	SC2C	SC3A	SC3B	SC3C
Route	HKI-TLL	HKI-TLL	HKI-TLL	RTM-SVIK	RTM-SVIK	RTM-SVIK	RTM-TBORG	**TBORG-RTM**	RTM-TBORG
Ship type	Pger	Pger	Pger	Tanker	Tanker	Tanker	Gcargo	Gcargo	Gcargo
Fuel type	Light	Light	Light	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy
Coating type	HC	**BC**	HC	HC	**BC**	HC	BC	BC	**FR**
IWC method	IWC + c	IWC + c	**IWC + no**	IWC + c	IWC + c	**IWC + no**	IWC + no	IWC + no	**No IWC**
IWC times /year	12	**2**	12	6	**2**	6	2	2	**0**
Off-hire costs/IWC	None	None	None	1 day	1 day	1 day	2 days	2 days	**None**
Theoretical fuel consumption t/h	3–4	3–4	3–4	1–2	1–2	1–2	4–5	4–5	4–5
Shipping hours (1000)	4–5	4–5	4–5	2–3	2–3	2–3	8–8.76	8–8.76	8–8.76
Time since coating (years)	Unset	Unset	Unset	Unset	Unset	Unset	4	4	4
IWC method in the past	Unset	Unset	Unset	Unset	Unset	Unset	Hard	Hard	**Unset**
WSA hm2	0.1–0.5	0.1–0.5	0.1–0.5	0.5–1	0.5–1	0.5–1	1–2	1–2	1–2

Table 2
The scenario-specific expected values for the different utility variables.

	SC1A	SC1B	SC1C	SC2A	SC2B	SC2C	SC3A	SC3B	SC3C
Fuel costs M€/year	8.055	8.127	8.055	1.388	1.362	1.388	13.785	13.785	13.433
Fuel costs €/h	1,790	1,806	1,790	555.2	544.6	555.2	1,645	1,645	1,603
IWC costs €/year	64,800	10,800	43,200	201,000	67,000	174,000	116,000	116,000	0
Coating costs €/year	19,200	13,200	19,200	48,000	33,000	48,000	66,000	66,000	156,000
CO_2 emissions Mkg/year	43.942	44.310	43.942	12.883	12.642	12.883	125.432	125.432	121.973
CO_2 emissions kg/h	9,765	9,847	9,765	5,153	5,057	5,153	14,968	14,968	14,555
Ecotoxico-logical release kg/year	0	139	0	0	254	0	430	430	0
Sediment ecotoxico-logical risk	0	50	0	0	50	0	100	50	0
NIS introduction risk/arrival	1.2	2.8	11.7	16.8	14.5	158.2	317.8	201.6	10.7

same number of IWCs) compared to SC2A. FR is the most expensive coating to apply, but free from the IWC costs, making the total IWC and coating costs (26,000 €/year) lower in SC3C compared to SC3A-B where also off-hire costs are considered.

The ecotoxicological release occurs only when BC is used (SC1B; SC2B; SC3A; SC3B). Naturally, the ship size and IWC times affect the released amount, being the highest in SC3A-B with a large ship (Table 2). When running the same scenarios without any IWC, the copper load decreased to 129 kg/y (SC1B), 238 kg/y (SC2B) and 366 kg/y (SC3A-B), showing 6.3–14.9 % increase in the toxic loading due to the IWC of BC.

The expected NIS introduction risk per each arrival is the highest in SC1C, SC2C and SC3A, all without the debris capture during IWC (Table 2). The expected NIS introduction risk level without the capture system (SC1C; SC2C) is roughly tenfold compared to the cases where the capture system is used (SC1A; SC2A). The NIS risk difference between SC3A and B arises from the opposite directions between the two ports. As there are less NIS in Trelleborg than in Rotterdam, the NIS introduction risk is higher for RTM - > TBORG (SC3A) also because the model assumes IWC occurring in the arrival port. The differences between SC3A and SC3B demonstrate the importance of careful consideration of the IWC location on a route.

The expected sediment ecotoxicological risk value is calculated for the arrival area and is over zero only when BC is used (i.e., in SC1B; SC2B; SC3A; SC3B) (Table 2). If the BC is used but the background sediment copper concentration is not above the threshold value 52 mg/kg in the arrival area (defined according to environmental quality standards for copper in marine sediments by Sahlin and Copper (2018) – see Section S6), the sediment ecotoxicological risk value is 50 (SC1B, SC2B, SC3B) but if the sediment copper concentration is above the threshold value, the risk value is 100 (SC3A). Since SC3A and B are identical but with opposite directions, they present different ecotoxicological risks despite the identical copper release rates. In addition, the IWC increasing the copper release is assumed to be performed only in the arrival port.

4. Discussion

Sustainable biofouling management requires tools supporting comprehensive, case-specific and multi-dimensional understanding. We constructed a MCDAM for multidimensional comparison of alternative biofouling management strategies for ships navigating in the BS - North Sea area. The model can be used to analyze ship- and route-specifically, how the different combinations of alternative hull coating types, IWC methods and the IWC frequency affect the costs of fuel consumption and biofouling management, the CO_2 emissions, as well as the risk levels due to biocidal release and potential new NIS introductions. The scenarios analyzed in this paper show that by careful consideration of the management strategy, both money and the environment can be saved.

Biofouling management pays back its costs via the decreased friction, leading to improved energy efficiency and lower fuel consumption of the ship, but also to decreased CO_2 emissions (Schultz, 2004; Schultz et al., 2011). In the analyzed scenarios, from the viewpoint of fuel consumption, the non-toxic HC and toxic BC are somewhat equally good options. BC is the lower-cost option when it comes both to its application and maintenance. However, as was commented by the interviewed ship operators, the savings in question are negligible in relation to the total costs of the operation (see e.g. the estimated yearly fuel costs shown in Table 2).

Our analysis shows the expected copper load from a passenger ship using BC is over 100 kg / year (SC1B) and even several hundred from bigger tankers (SC3A-B). This is in line with the TBT (tributyltin) release data published by HELCOM, showing a container ship releases about 100 kg of TBT annually (see Watermann and Eklund (2019) and references therein). Further, Watermann and Eklund (2019) estimated the annual input of BC compounds from the whole BS fleet can be even 44.4 t. Given the intense marine traffic of the BS, even a relatively small decrease in the biocidal release per ship would make a big difference annually. Copper is toxic for marine ecosystems (Martins et al., 2017), and the low salinity level of the BS can increase its toxicity (Brooks and Waldock, 2009; Luoma and Rainbow, 2008; Nasir, 2014; Ragnvaldsson et al., 2022).

Conducted frequently during the growing season, IWC can remove the organisms attached to a ship's hull before their maturation and breeding (Sherman et al., 2020). Frequent IWC also prevents biofouling level from exceeding the soft fouling (Scianni and Georgiades, 2019). Capture of the organic debris increases the IWC price by approximately 50 % but based on Hopkins and Forrest (2008) and the biofouling experts who participated our study, IWC without the capture system may cause higher NIS introduction risk than an uncleaned hull, by releasing the attached individuals and gametes. This logic is represented in the MCDAM (section S4, definition of the *NIS introduction risk value*). According to the model, without the debris capture the NIS introduction risk can be tenfold compared to an IWC with a capture device. This estimate is in line with the previous studies considering the efficacy of the capturing (Tamburri et al., 2020). The risk is even higher with heavily fouled ships sailing from outside the BS and performing IWC without a capture system inside the BS (see SC3A vs. SC3B).

Even without the IWC, species can detach from the hull or spread gametes (Gollasch, 2002; Gollasch and Leppäkoski, 2007; Hewitt et al., 2009). In our MCDAM, whenever environmental similarity between the departure and arrival areas occurs, the risk of each potential new NIS introduction is considered with an equal weight. In reality, some of the species have less severe or no verifiable impacts, or the availability of free ecological niches in the arrival area may be low, decreasing the probability of successful settling. In the worst case, however, NIS can have devastating consequences in the marine environment (see Berezina et al. (2011)). The MCDAM follows the viewpoint of the HELCOM Baltic Sea Action Plan (HELCOM, 2007) stating all new NIS introductions should be avoided.

SC3A-B demonstrated the importance of careful consideration of the IWC location in terms of both NIS introduction and ecotoxicological risks. Especially if IWC is conducted without the capture system, it is important to be aware of the NIS introduction potential on a route. Brushing the BC during IWC increases the copper release even by 15 %, thus also the ecological resilience of the area against the copper loading is worth considering. In our MCDAM the areas with the highest sediment background concentrations are given higher risk value than the areas, where the background concentration does not yet exceed the threshold value. The logic is not univocal, however, but it might also be justifiable to suggest focusing harmful activities to areas that are already ruined. Most importantly, the use of BC should be carefully considered and whenever applied, its biocide content should be adjusted to the salinity of the operation area. In some parts of the BS, paints with overly high concentrations are used (Lagerström et al., 2018), causing additional ecotoxicological stress without any extra benefits.

As in SC3C (vs. SC3A), the novel FR coatings appear as a promising solution without IWC costs or copper release. However, more research is needed concerning their ecological effects, since some studies indicate potential eco-toxicity (see Piazza et al. (2018) and references therein) despite the absence of copper. Further, the softness of the FR coatings makes them applicable only in the ice-free conditions (Hu et al., 2020) of the southern BS and North Sea areas. Hence, there is still a need for new innovative biofouling management solutions suitable for the BS conditions.

Our analysis is based on the expected utilities. However, uncertainty associated with these estimates vary. BNs offer good possibilities to study the measures related to uncertainties and help to realize how much uncertainty is behind the expected utilities. To compare the relative level of uncertainty, we represented the utility nodes as random variables and calculated the probability distributions behind the expected values utilities (see Table S10). To represent the scenario-specific uncertainties, we present the coefficient of variation (CV) of those distributions in Section S7 (Fig. S1). The uncertainties associated with the fuel costs and carbon dioxide emissions are the highest in SC2, the low number of IWC increasing the uncertainty related to biofouling pressure and further on the fuel costs and emissions. The uncertainty associated with the IWC costs is the highest in SC1A where the high number of IWCs is performed with a capture system. The highest uncertainty of the NIS introduction risk is in SC2C where a HC with only six IWCs without a capture system is used. The relatively wide intervals (i.e. coarse discretization) of the variable *wetted surface area,* representing the ship size, increases the uncertainty in many of its descendant nodes, thus in the future the number of its intervals could be increased.

There are no harmonized rules among the BS countries, when it comes to the IWC practices. IWC of the BC-treated hulls is still an established procedure and allowed by some countries and the use of a capture system is optional (Krutwa et al., 2019). According to the interviewees of this study, the high competition between IWC companies and the lack of harmonized regulation in the BS have resulted in lower IWC costs than in many other marine areas. Therefore, ships sailing in and out of the BS are tempted to perform the IWC in the BS, increasing the related risks. An IWC company representative stated that, since the IWC price can be up to 60 % higher with the so far optional capture system, only a few shipping companies utilize the option.

The MCDAM is intended to support especially the selection of a case-specifically best biofouling management strategy. It is the first such model considering the economic and environmental perspectives in parallel. The model allows its user to study two main biofouling management methods (coating and IWC) together, providing scenario-specific estimates on monetary costs (biofouling and fuel consumption), CO_2 emissions, eco-toxicological release (copper load) and NIS introduction risk. Although these measures are not directly comparable nor commensurable, we argue it is important to make all the aspects of the management decisions visible to support transparent and sustainable decision making.

To evaluate the usefulness, usability and development needs of the MCDAM, five test-use workshops were organized online for potential end-users (N=10), including representatives of environmental and maritime authorities, and shipping and IWC companies (Luoma et al., 2021c). The model was seen to increase holistic understanding concerning the multi-dimensional management problem. Its potential in increasing the awareness concerning the environmental aspects of the biofouling management among both the shipping companies, but also their clients, was seen as an asset. The MCDAM was even mentioned as a potentially valuable tool in supporting preparations of the biofouling management plan recommended by International Maritime Organization IMO (2011) and the future legislation regarding the restrictions of certain biofouling management methods. Part of the test-users hoped for a more user-friendly interface (than the Hugin platform) to ease the use of the model (Luoma et al., 2021c). In addition, since the biofouling management costs and fuel costs vary in time and space, one test user suggested adjustments that would allow the model user to define the costs more easily.

Currently the MCDAM considers the NIS introduction risk between the departure and destination port only, whereas in reality the risk may occur during the whole voyage (Murray et al., 2012). The principle of the FR coating is actually based on the organisms' release during the voyage, which is not considered as a risk in the current model version. The present MCDAM also assumes the release rate of copper, as well as the accumulation rate of biofouling are standard in different parts of the BS and throughout the growing season. Whenever more data on the route-specific biofouling accumulation and copper release rates is available, the model could be improved in that respect. Further, the current world situation increases the uncertainty related to fuel price. In the present model, the end-user can modify the fuel prices but in the future also a random variable considering the uncertainty related to fuel price could be added.

Finally, the MCDAM works best for ships sailing on fixed routes, since the modeled situation contains a single voyage which is repeated multiple times a year. This also creates challenges in calculating the NIS introduction risk especially when IWC without a capture system occurs. The NIS introduction risk/arrival is low if the IWC occurs frequently enough (12 times/year), even without a capture system. This is because if IWC occurs frequently, the attached organisms are not given time to grow nor reach their maturity. This is something the end-user should understand.

Aroused in the interviews of this study (Luoma et al., 2021a; Luoma et al., 2021c), only recently the shipping industry has started to realize the magnitude of the slightest biofouling layer has in increasing the annual fuel costs. The slowly increasing fuel consumption is often overlooked (Pagoropoulos et al., 2017) and the value of regular cleaning of only slightly biofouled hulls is underestimated if attention is not paid on the annual impacts. In addition, it came up in the interviews that the shipping companies are willing to make greener choices in their operation if they are economically sensible but experience they lack knowledge about the sustainability of different management options. The presented MCDAM supports sustainable biofouling management by helping to see the bigger picture, both in terms of the various impacts to be considered while choosing the management strategy, and the magnitude of the impacts on a yearly basis.

5. Conclusions

Based on the developed MCDAM, biocidal-free FR coatings offer a promising alternative in ice-free areas such as in the southern BS. However, more studies on their ecological effects are still needed. As the softness of the FR makes its use impossible in ice conditions, a biocidal-free HC with a regular IWC applying a capture system seems to be the most promising option for most of the BS area. With this strategy the eco-toxicological impact and NIS introduction risk are both low, but the solution still effectively reduces the biofouling, lowering the fuel consumption and air emissions. The strategy is not the cheapest one but the difference from the biocidal coating strategy is very small in terms of the total operation costs of the shipping companies. For some ship types, such as tankers, regular IWC can be very expensive and complicated to arrange. In such cases, the BC can appear as a reasonable solution. However, special attention should be paid to adjusting the copper concentration and release rate from the coating to the salinity conditions of the BS, to avoid the overuse of the biocides. Finally, there is still a need for novel innovative biofouling management methods suitable for the BS conditions and for harmonized international regulation considering the biofouling management.

CRediT authorship contribution statement

Emilia Luoma: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mirka Laurila-Pant:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Elias Altarriba:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing

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Data availability

The link to the model code has been shared in the manuscript (line 223)

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 A. Supplementary data

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