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Support for the Selection of Environmental Impact Abatement Equipment in the Early Stage Design

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Abstract

Stricter regulations for shipping on the emission to air and water are introduced. To deal with this, a part of the Horizon2020 NAVAIS project is devoted to the identification of relevant regulations and the design of a tool to select the optimal combination of abatement options to achieve or go beyond the limits set by these regulations. It is an early-stage design tool, which includes the mutual influences of abatement options on each other, allowing/giving a deeper understanding of trade-offs to be made. The results of this tool show the trade-off between emission abatement and costs.

1. Introduction

The environmental impact of shipping is significant, *Buhaug et al. (2009)*. A process of further and further regulating both emissions to the air and to the water is ongoing (e.g. EU's Good Environmental Status). The most well-known emissions are greenhouse gasses (GHG), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and particulate matter (PM), *Buhaug et al. (2009), EEA (2012)*. Also, pollution of the water with sewage or oil is banned, more recently ballast water needs to be treated to avoid spreading organisms into new habitats, *IMO (2004)*. Less known is noise pollution, which is receiving more attention recently as well, *McKenna et al. (2012)*.

Methods to comply with these regulations and limitations are not evident. In many cases, reducing one element increases another. For example, reducing NO_x will result in either more PM when working with the engine load, or it will result in more CO_2 when actively filtering the exhaust gasses. Furthermore, all these systems require space (besides additional investments and running costs) in the vessel and should be considered in an early stage of the design to not end up with space issues in a later design stage. This was also recognised by the European Commission and has led to the NAVAIS project. Within this project, a tool to support this early stage design with a selection tool was developed. This tool was named TEchnology Selection Tool for Emission Reduction (TESTER). In Section 2 both the relevant regulations and already available tools and approaches will be discussed. In Section 3 the methodology is described in detail, followed by two applications in Section 4. Finally, Section 5 will conclude and give recommendations for further research.

2. Literature Review

The literature review contains two important parts, the first part is an overview of regulations and an assessment of the relevance and type of compliance especially considering the early stage of the design. The second part focusses on identifying relevant research on how to select the best combination of equipment to comply with the selected regulations.

2.1. Regulations

Three different levels of regulations are in force in the maritime sector; international, national and local. For this study, the international (International Maritime Organisation, IMO) regulations are assessed. To identify the potential impact of national regulations, also the regulations of Canada, Norway and the European Union (EU) have been studied. It was currently beyond the scope of the project to also study local legislations, which can differ per port or state. Local regulations are relevant when designing for a concrete situation and the option to include specific local regulations is a requirement for the TESTER development.

Table I shows all identified emissions to either water or air. The first column identifies the type of emission, the second column refers to the relevant regulation. In some cases local regulations are added to show stricter limits may apply. These limits are presented in the third column. In some cases, there is not one specific limit, but a formula. Especially in the case of the EEDI, NO_x and URN (underwater radiated noise), the limits are usually represented graphically. These will not be repeated in this paper; for these figures, we refer to the reference indicated in the fourth column. Finally, in the last column, the applicability for the NAVAIS project, but also for the TESTER tool is indicated. If a "No" is indicated, the text behind the arrow shortly explains the reason for this. The most common reason is that the implementation has no interaction with other systems, however, TESTER's key contribution is the integration of system impacts. In several cases the early-stage design is not the moment to address an issue as more detailed information is required to estimate the impact. For checking compliance with underwater radiated noise (URN) limits, for example, details of the propeller design are needed, which are not available in the early design phase. Finally, in some cases, no limits were identified and therefore the emissions will not be included.

Table I: Identified legislation for emissions to air and water from ships

Environmental impact	**Regulations**	**Limit**	**References**	**Applicable for TESTER**
Oil	MARPOL Annex I, Ch.3, Pt. C, Reg. 15	<15 ppm	*IMO (2017)*	Yes
	Canada – TP12301	<5 ppm		
Noxious liquid substances	MARPOL Annex II	Various limits	*IMO (2017)*	No => No system dependency
Harmful substances in packaged form	MARPOL Annex III	List of threats	*IMO (2017)*	No => No system dependency
Sewage	MARPOL Annex IV	0.00926*V*D l/min	*IMO (2017)*	Yes
	Canada – TP15211E, Annex I, Sec. 5.3	<14 Particle count/ml		
Garbage	MARPOL Annex V	Various limits	*IMO (2017)*	No => No system dependency
Nitrogen Oxides (NO_x)	MARPOL Annex VI, Ch. 3, Reg. 13	Variable limit	*IMO (2017)*	Yes
Sulphur Oxides (SO_x)	MARPOL Annex VI, Ch. 3, Reg. 14	0.1 %	*IMO (2017)*	Yes
Particulate Matter (diameter smaller than 2.5 µm, $PM_{2.5}$)	MARPOL Annex VI, Ch. 3, Reg. 14	0.5 %	*IMO (2017)*	Yes
Volatile Organic Compounds (VOC)	MARPOL Annex VI, Ch. 3, Reg. 15	No limit for methane-slip (LNG)	*IMO (2017)*	Yes => the impact can be established even without legal limits.
Carbon Dioxide (CO_2)	MARPOL Annex VI, Ch. 3, Reg. 20/21–EEDI	Variable limit	*MEPC (2012), IMO (2017)*	Yes
Underwater radiated noise (URN)	IMO MEPC.1/Circ. 833	Currently: all voluntary.	*DNVGL (2018b), IMO (2014b, JOMOPANS (2017), GM (2017), OSPAR (2017), LR (2018), RINA (2017), ABS (2018), POV (2017), BV (2018)*	No => More detailed design required
	EU Marine Strategy Framework Directive for Good Environmental Status – Descriptor 11			
	OSPAR/JOMOPANS, BIAS, Green Marine, Classification			

Above water noise	IMO Resolution MSC.337(91)	Only local	*IMO (2014a)*	No => More detailed design required
Surface waves	Only local	Limits on wash or speed	*Bolt (2001), Feldtmann (2000), Kirkegaard et al. (1999), Murphy et al. (2006), Raven and Valkhof (1998)*	No => N system dependency, but hull shape dependent
Electromagnetic radiation	International Commission on Non-Ionizing Radiation Protection (ICNIRP), International Committee on Electromagnetic Safety (ICES)	Regulated at the equipment level	*Mitson (1995)*	No => Equipment is approved separately
Heat	No legislation found	N/A	N/A	No => No legislation
Light – visible / Infrared (IR)	Part C of COLREG72, CAP437 and Annex 14, IMO SOLAS	Only requirements on required light, no limitations. IR limitation focus on naval ships only.	*Authority (2016), Commandant (1999), MSC (2006)*	No => No limitations
Ballast water	BWM-2004, D-2 standard	D-2 Standard	*IMO (2004)*	No => Local operations

2.2. Ship Design Solutions

In the maritime industry, the use of an optimisation algorithm for the selection of abatement options can be traced back to the research done in 2005 by *Winebrake et al. (2005)*. This study uses a nonlinear optimisation algorithm to find a cost-effective combination of technologies for ferries. A lot of attention has also been paid to this optimisation problem by *Balland et al. (2010,2012,210*4,2015). These authors use an integer linear optimisation algorithm for the selection of abatement options. They also addressed several decision factors such as changing regulations over time, uncertainty in emission reductions and the simultaneous selection of the mechanical systems and other aspects. The simultaneous selection of abatement options and machinery systems is also an option, *Trivyza et al. (2018), Wagner (2005)*. In their study, they use a genetic algorithm to find the most cost-effective combinations of energy systems over the ship's life cycle. This indicates that a variety of algorithms have already been applied for this type of optimisation problem. A key advantage of OR (Operations Research) techniques is that a clear answer is provided, the major drawback is the amount of data required to evaluate and select options.

The Multi-Criteria Decision-Making (MCDM) approach solves this data issue by working with relative weights, rather than absolute numbers. In that way, multiple unrelated aspects can be combined. The analytical hierarchy process (AHP), which uses a pairwise comparison to determine the weight of each element and choice is the most popular, *Hansson et al. (2019), Ren and Lützen (2015), Schinas and Stefanakos (2014), Yang et al. (2012)*. Distance-based and other weight-based methods have also been applied, *Corbett and Chapman (2006), Ölçer and Ballini (2015), Vakili (2018)*. Despite the multi-criteria approaches used in the developed models, they always contain some degree of subjectivity. Therefore, an optimisation approach was chosen for the selection tool. For clarity, the studied approaches have been combined in an overview in Fig.1 (left).

In addition to the selection approaches of individual aspects, it is also important to consider how to select the optimal combination. As can be seen in Fig.1 (right) three main approaches were identified in the literature. Some are purely economic, such as a Net Present Value (NPV), *Balland et al. (2015), Corbett and Chapman (2006), Ölçer and Ballini (2015), Schinas and Stefanakos (2014)* calculation, or life cycle costing (LCC), *Trivyza et al. (2018), Wang et al. (2005)*. Others only consider the environmental aspects in a life cycle assessment (LCA), while two mixed approaches were identified, cost-benefit analysis (CBA), *Balland et al. (2014), Bari et al. (2011), Hansson et al. (2019), Ren and Lützen (2015), Vakili (2018), Yang et al. (2012)* and Marginal Abatement Cost Curves (MACC), *Calleya et al. (2015), Wang et al. (2010), Winebrake et al. (2005)*. Interesting are the options offered by LCC and LCA to compare the environmental impacts of different kinds with each other, either using the concept of costs to society, or an indicative value such as ecopoints.

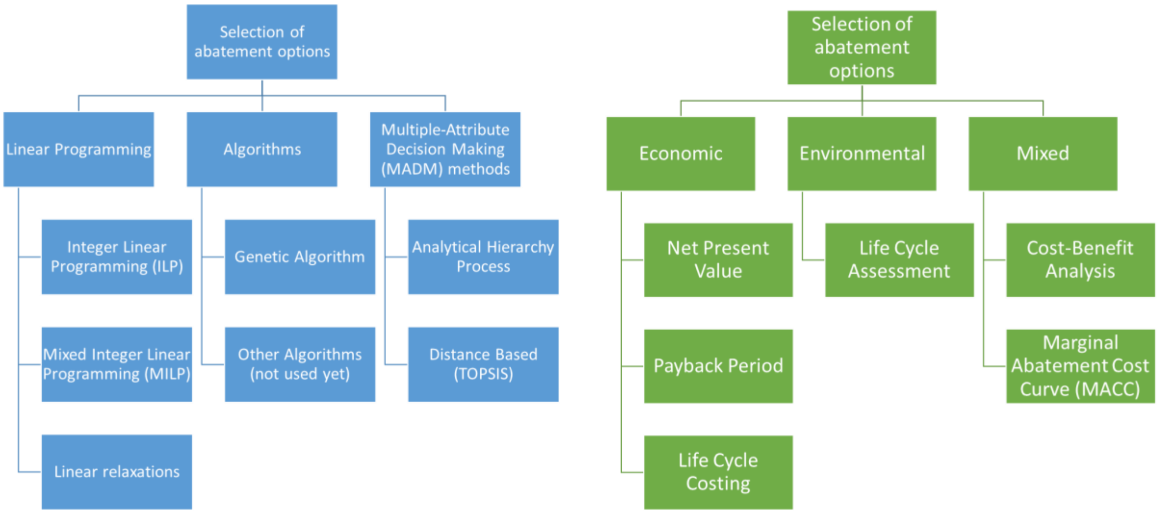


Fig.1: Taxonomy of decision-making techniques used in the reviewed literature. Optimisation (left) and Evaluative (right)

The MACC compares costs and impacts as measures are sorted by costs and the environmental impact is shown. In a MACC graph, the achieved impact reduction is shown on the horizontal axis and on the vertical the costs per unit of reduction is presented. The measures are sorted by the costs (cheapest first) and the costs could even be negative. This way a shipowner can identify options that will not only reduce the impact but also save money. A second stage could be to increase the impact reduction until a break-even is reached between costs and profits of emission reduction measures. Although the MACC is a very useful first step, a crucial element is missing in the selection process; some abatement options are mutually exclusive or influence each other. Also, the available methods are often limited to GHG, without taking into account other regulations and impacts.

Finally, based on the literature described above, four major elements for the abatement can be identified. The first is the energy systems, these deliver the power for the activities of the ship. The main groups within these elements are internal combustion engines, batteries and fuel cells. The second, related, element is the fuel. The main groups identified here are traditional fuels, transitional fuels (biodiesel, LNG) and alternative fuels. The last group currently has a low Technology Readiness Level (TRL) in general, *Hansson et al. (2019)*. The next element is the energy efficiency increasing options. Primarily ship design and additional power and propulsion systems (waste heat recovery, solar panels, sails) fall in this group. The fourth element is the emission-reducing systems. Here, the primary methods are related to the engine (reducing the creation of emission), while the secondary measures are related to capturing emission in the exhaust gas. An overview of the systems with their advantages (third column) and disadvantages (last column) is presented in Table II (FC is Fuel Consumption).

Table 2: Abatement Systems

Main Element	System	Advantage	Disadvantage
Energy systems	Diesel engine	High specific power	Noise and high NO_x emissions
	Gas engine	High specific power and lower NO_x	Noise and CH_4 emissions
	Batteries	No emissions and noise,	Low specific power and energy
	Ultracapacitor	High specific power and no emissions	Low specific energy
	Flywheel	High specific power and no emissions	Complex design, not for main propulsion
	Hydrogen fuel cell	No emissions and low noise	Low specific power
Fuels	Diesel fuels (high sulphur content)	High energy density; low fuel cost	High SOx, CO_2 emissions
	Diesel fuels (low sulphur content)	High energy density, low SO_x	High fuel costs, CO_2 emissions
	LNG	Low SO_x; lower CO_2, PM and NO_x	Dimensions and costs, CH_4 slip
	Biofuels	Lower CO_2; No system impacts	Increase of FC, affects (fuel) system
	LPG	Low SO_x; lower CO_2, PM and NOx	Safety, Butane slip
	Methanol	Reduction of CO_2, NOx and PM	Corrosive, low energy density
	Ammonia	No CO_2	Low energy density, toxic
	Hydrogen	No emissions in fuel cell	Low energy storage density
energy-efficiency	Lightweight construction	Reduction of FC	High investment costs
	Optimisation of hull form	Reduction of FC	High investment costs, in refit
	Hull coating	Reduction FC and URN	Extra investment
	Air (cavity) lubrication	Reduction of FC	Less effective off-design
	Waste Heat Recovery (WHR)	Reduction of FC	High costs and efficiency
	Propeller (flow) optimisation	Reduction of URN and/or FC	Trade-off between URN and efficiency
	Wind recovery systems	reduction of FC	Limited operational envelope and space
	Solar panels	reduction of FC	Low and variable energy yield
	Energy-efficient lighting	Reduction of FC	-
emission-reduction	Humid Air Motor (HAM)	Reduction of NO_x	Increase of FC
	Fuel Water Emulsion (FWE)	Reduction of NO_x and PM	Increase of FC, corrosive
	Direct Water Injection (DWI)	Reduction of NO_x	Increase of FC
	Exhaust Gas Recirculation (EGR)	Reduction of NO_x and CH_4	Increase of FC and PM
	Selective Catalytic Reduction (SCR)	Reduction of NO_x and PM	Increase of FC
	Diesel Particulate Filter (DPF)	Reduction of PM	Increase of FC, sulphur
	Diesel Oxidation Catalyst (DOC)	Reduction of PM	Sulphur in fuel
	Exhaust gas scrubber	Reduction of SO_x and PM	Dimensions, Increase of FC

3. Methodology

In this section, a selection of approaches and methods will be made based on the advantages and disadvantages identified in the literature study. Also, the setup of the TESTER (TEchnology Selection Tool for Emission Reduction) tool will be discussed.

The chosen approach should deal with four important elements:

1. The model includes the influences of systems on each other.
2. The model evaluates more environmental impacts than only GHG.
3. An optimisation is preferred over MADM and
4. The selected reduction options are all available in the model.

These requirements have a huge impact on the choice of optimisation approaches as the problem becomes highly non-linear, excluding LP (Linear Programming) solutions. To combine or compare the environmental impact, the costs-to-society (CTS) approach was taken from the LCA and LCC approaches. As external costs are primarily to compare different impact categories and not intended to function as real costs for the shipowner, the choice was made to use a multi-objective optimisation. This is then split between external costs and direct expenses for the owner (investment in equipment and operational costs). The first objective is the minimization of internal (company-related) costs, while the second objective is the external (environment-related) virtual costs. This allows the different costs to remain separated and to be able to adjust their impact using weights. The four requirements implicate that the model can deal with complex interactions and administrate various emissions side by side.

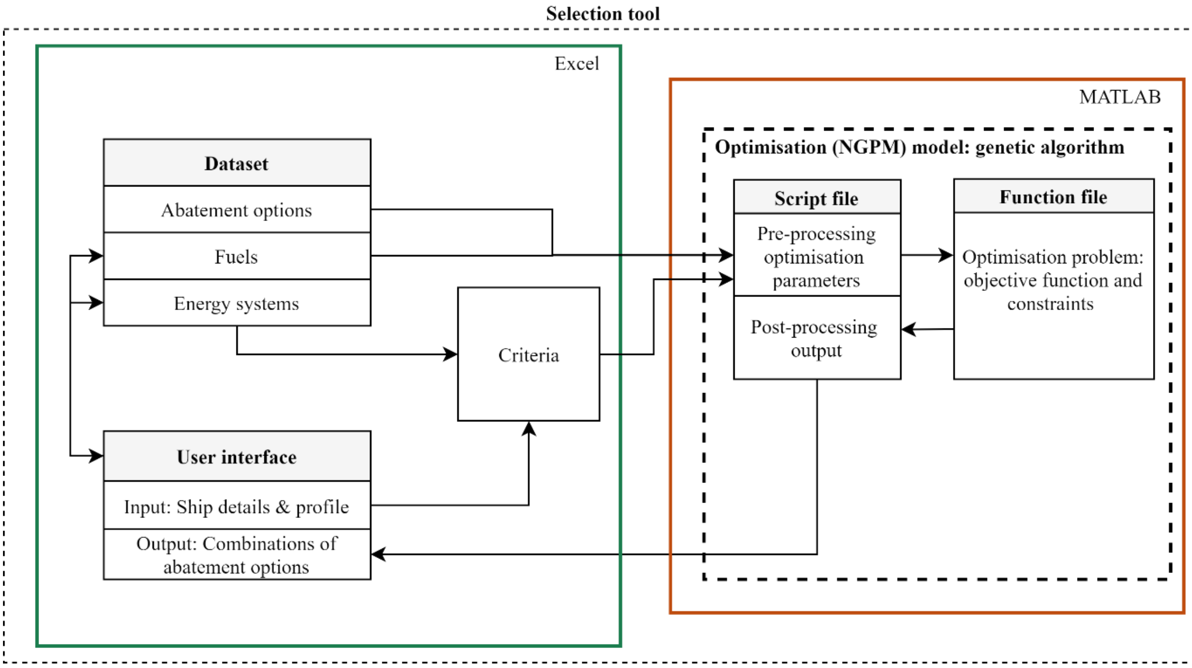


Fig.2: Flow chart of the selection tool

The result is TESTER; a model with two components the input, output and background data is managed in Microsoft excel® for relatively easy use and control. The optimisation is done in Mathworks MATLAB® making use of the non-dominated sorting genetic algorithm II solver. The solver is suitable for the problem described, although a more in-depth study of potential solvers should be executed in the future to identify the optimal solver. The final model is presented in Fig.2.

The actual implementation and verification of this model can be found in the publicly available deliverables D4.1 and D4.2 of the NAVAIS project, *Pruyn (2019).*

4. Case Studies

The NAVAIS project focusses on improving the environmental impact of a family of road ferries and a family of workboats. Due to this focus, TESTER was tested on two instances, one of each ship type. In Section 4.1 the road ferry and the optimisation results will be discussed, whereas in Section 4.2 the selected workboat and optimisation will be discussed.

4.1. Road Ferry

The electric "Road Ferry 9819" has been chosen as the reference vessel for the case study because it has similar characteristics to the intended concept design in the NAVAIS project. This type is also a double-ended ferry configuration, which has a comparable passenger/car capacity and has full-electrical propulsion.

Some information about this reference vessel is given in Table III and Fig.3. The energy system configuration of the road ferry 9819 is full-electric, in which the four azimuth thrusters are electrically driven. The road ferry has back-up diesel generator sets which are required by SOLAS regulations for passenger vessels as an emergency generator for redundancy, but they are not used during normal operation. Additionally, the reference ship is designed for an operational area that can have ice conditions. In that case, the diesel generators can be used to give an extra boost in addition to the power obtained from the batteries. However, the aforementioned scenarios are rare, so it can be assumed that the road ferry will mainly sail electrically with the power being obtained from the batteries.

Fig.3: Damen road ferry 9819, *Damen (2020a)*

Table III: Ship specifics (Road ferry 9819) and operational profile, *Damen (2020a)*

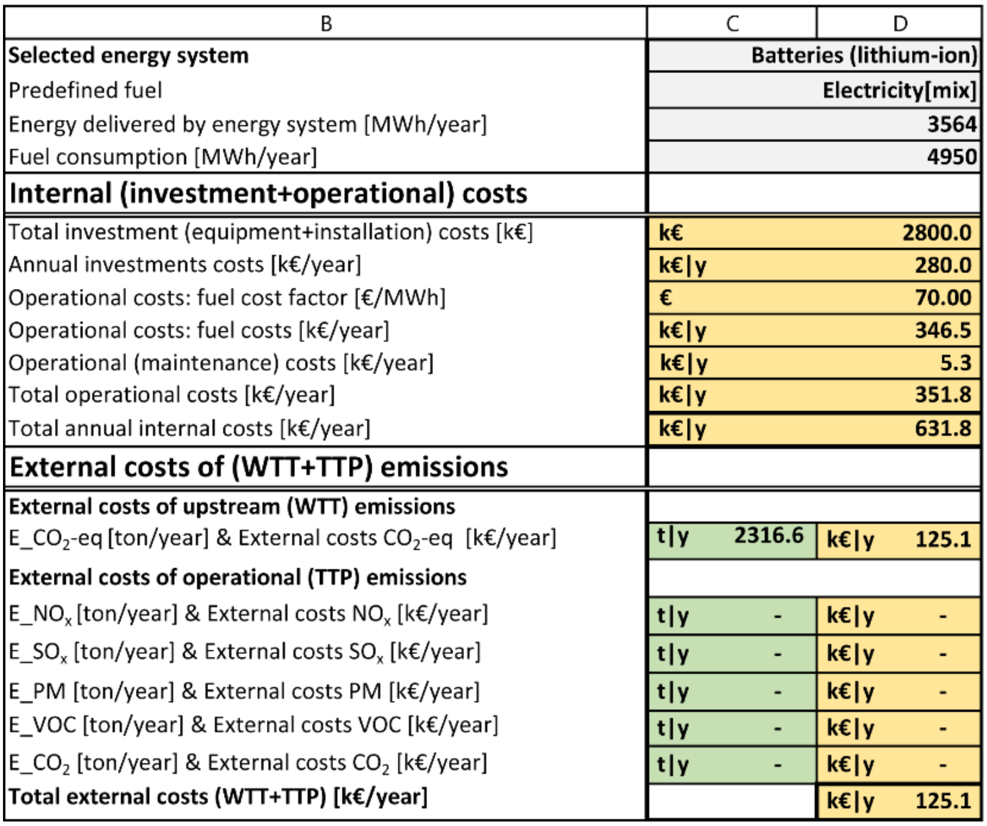
Length	98.4 m
Beam	20.2 m
Azimuth thrusters	4*520 kW
Diesel generator sets	2*565 ekW
Battery pack	4000 kWh
Free Sailing	15 min
Manoeuvring	4 min
At berth/charging	11 min

Therefore, only the performance of the full-electric battery mode is evaluated as the benchmark. The environmental and economic performance of the reference vessel is evaluated based on the annual operational profile. The annual profile is based on 97% availability, in which 10 days per year can be reserved for maintenance work. The operational profile is divided into three conditions: free sailing, manoeuvring, and at berth. The assumed operational profile for a one-way trip of 30 minutes is given in Table III. At berth, the electric ferry will use shore power for recharging the batteries.

The assumed energy consumption is estimated at around 550 kWh per trip. This is based on the required propulsion power to drive the four azimuth thrusters (e.g. distribution of 70% aft and 30% forward), an effective efficiency, trip time and an assumed auxiliary load (~50 kWh per trip). It is assumed that the road ferry is operational for 15 hours a day, resulting in a total of 30 trips. This gives a total energy consumption of 16.5 MWh per day and 5841 MWh per year. 85% of the annual energy consumption is used for propulsion power and the other 15 % is used for the auxiliary energy consumption such as Heating Ventilation and Air Conditioning (HVAC).

The internal costs and external costs of the benchmark energy system are summarised in Table IV. This table shows the build-up of the internal costs on an annual basis, which is a summation of the annual depreciation and interest costs and the operational costs. Furthermore, it shows that the annual investment costs are of the same order as the operational costs (280.0 k€ investment costs and 351.8 k€ Operational costs). The benchmark electricity is assumed to be produced from a European mix of energy sources, including more polluting sources such as coal. This electricity has upstream emissions (WTT) from the production, which are based on a European average carbon intensity (emission) factor of 466 gCO2-eq/kWh, *Gilbert et al. (2018), Moro and Lonza (2018).* A European average industrial electricity (mix) price of 70 [€/MWh] is used, which is based on values from, *EC (2019).* TTP are emissions of the energy system on board. The Costs to Society (CTS) factors are taken from, *Lafeber (2019).*

Table IV: Benchmark performance of the road ferry



B	C	D
Selected energy system	**Batteries (lithium-ion)**	
Predefined fuel	**Electricity[mix]**	
Energy delivered by energy system [MWh/year]	**3564**	
Fuel consumption [MWh/year]	**4950**	
Internal (investment+operational) costs		
Total investment (equipment+installation) costs [k€]	**k€ 2800.0**	
Annual investments costs [k€/year]	**k€|y 280.0**	
Operational costs: fuel cost factor [€/MWh]	**€ 70.00**	
Operational costs: fuel costs [k€/year]	**k€|y 346.5**	
Operational (maintenance) costs [k€/year]	**k€|y 5.3**	
Total operational costs [k€/year]	**k€|y 351.8**	
Total annual internal costs [k€/year]	**k€|y 631.8**	
External costs of (WTT+TTP) emissions		
External costs of upstream (WTT) emissions		
E_CO$_2$-eq [ton/year] & External costs CO$_2$-eq [k€/year]	**t|y 2316.6**	**k€|y 125.1**
External costs of operational (TTP) emissions		
E_NO$_x$ [ton/year] & External costs NO$_x$ [k€/year]	**t|y -**	**k€|y -**
E_SO$_x$ [ton/year] & External costs SO$_x$ [k€/year]	**t|y -**	**k€|y -**
E_PM [ton/year] & External costs PM [k€/year]	**t|y -**	**k€|y -**
E_VOC [ton/year] & External costs VOC [k€/year]	**t|y -**	**k€|y -**
E_CO$_2$ [ton/year] & External costs CO$_2$ [k€/year]	**t|y -**	**k€|y -**
Total external costs (WTT+TTP) [k€/year]		**k€|y 125.1**

The optimisation algorithm is tested for different population sizes and numbers of generations, as this is case dependent. The population size largely determines the variability in the solutions. However, a larger population size together with a larger amount of generations increase the solution time. For this type of decision context, the emphasis is not on the exact solution, but on scanning and finding a feasible design space for possible combinations within a reasonable calculation time. Using the MATLAB Graphical User Interface (GUI), it was determined after how many generations the algorithm had converged. Furthermore, the number of solutions and solution time were noted.

The test overview for the road ferry is presented in Table V. It shows that the optimisation run has often converged in about 10 generations, therefore the number of generations for the optimisation is set to 20 to include a margin. Furthermore, it appears that the results remain the same if the population size increases. Therefore, the selected population size is 50.

Table V: Determination of population size and number of generations for road ferry case

Population Size	**Nr. Of generations**	**Convergence after generation.#**	**Nr of Solutions**	**Solution Time (s)**	**Obj 1 (k€/year)**	**Obj 2 (k€/year)**
50	10	10	18	3.3	673.6	92.6
50	20	15	28	6.9	664.4	95.5
50	30	13	25	7.6	664.4	95.5
100	20	10	21	11.4	664.4	95.5
200	20	11	21	15.6	664.4	95.5

The final solution is visualised in Fig.4. This figure shows the benchmark performance in terms of internal costs and external costs. It shows how the combinations (blue circles) lead to a reduction of the external costs of emissions and how these combinations impact the internal costs. In the output, two sets of solutions can be distinguished. These solutions are studied in more detail below. In Table VI the solution with the lowest internal cost (far left bullet) and the solution with the lowest external costs (far right bullet) are compared to the initial benchmark.

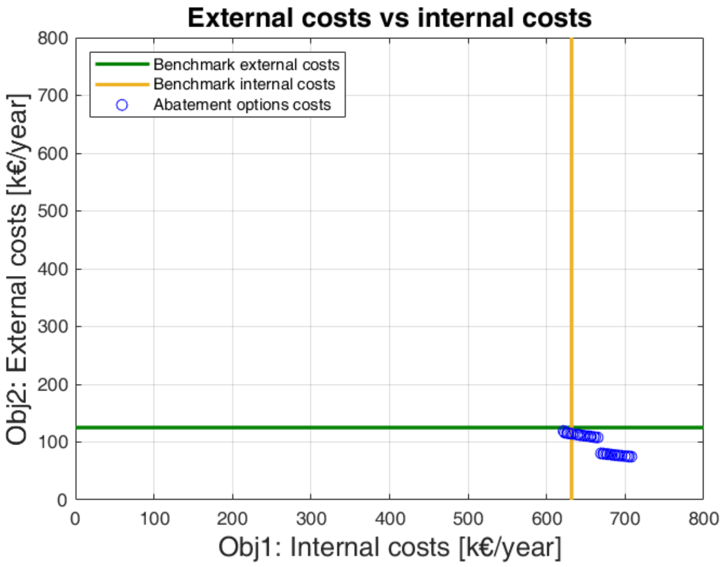


Fig.4: output case study road ferry relative to the benchmark

Table VI: Comparison of the optimised solution with the benchmark for the road ferry.

Element	**Benchmark**	**Min. Internal Costs**	**Min. External Costs**
Internal Costs (k€/year)	631.8	621.6	707.7
External Costs (k€/year)	125.1	119.2	74.8
Abatement Options			
System 1	Electricity [EU mix]	Electricity [EU mix]	Electricity [Renewable energy]
System 2		Hydrodynamically optimised hull form and appendages	Hydrodynamically optimised hull form and appendages.
System 3			Propeller optimisation - Higher efficiency, higher URN
System 4			Solar panels

For the solutions with the lower internal costs, hydrodynamic design optimisation is responsible for a decrease in overall costs, as this is a relatively cheap option, but could impact the operational costs positively for many years. In the minimal external costs, the solar panels are an investment in the future; it will make the ship more expensive, but the ship's impact is reduced further. In this situation, "green" electricity is also considered. In a sensitivity study, it was identified that both lowering the costs of green electricity and lowering the upstream emissions would cause the optimiser to find more optimal solutions adopting green electricity instead of the current "grey" electricity mix currently available in Europe.

Since the ferry was already electric, no major improvements were achieved in these optimisations. Still, two relevant abatements systems or approaches were identified to lower emissions further without increasing the benchmark costs: Hull Optimisation and High-efficiency propellers. The latter will most likely increase the Underwater Radiated Noise, but without any strict regulations available yet, the efficiency gain seems preferable at this moment in time.

4.2. Workboat

The Damen workboat "UV 4312", Fig.5, Table VII, is chosen as the reference vessel for this case study because the UV 4312 has similar dimensions to the intended NAVAIS subject. The vessel has a gross tonnage of 499 GT. The energy system configuration is diesel-electric, in which two azimuth thrusters with ducted propellers are electrically driven by two electric motors. The vessel has three diesel gensets (Volvo D16) with a rated power of 470 ekW each, *Damen (2020b)*. The reference vessel also has a smaller diesel genset (Volvo D7) of 139 ekW. This small diesel genset can support the main diesel gensets or provide the power for smaller loads. The diesel-electric configuration with a total of four diesel gensets provides flexible power supply for the 750 kW propulsion system and other loads on board. The high-speed diesel engine is the most suitable type for this type of workboat, because of the power range and since there is limited space in the machinery room.

Fig.5: Reference vessel Damen workboat UV 4312, *Damen (2020b)*

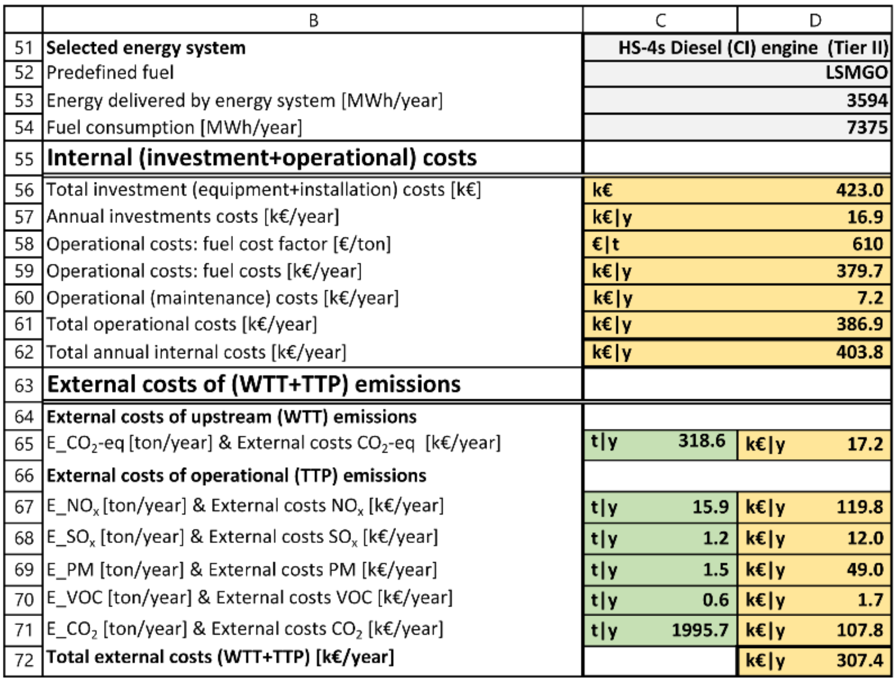
Table VII: Ship specifics (UV 4312) and operational profile, *Damen (2020b)*

Length	43.27 m
Beam	12 m
Azimuth thrusters	2
Bow thrusters	1
Electric motors	2*375 ekW
Main diesel gensets (Volvo D16)	3*470 ekW
Small diesel genset (Volvo D7)	1*139 ekW
Free sailing	5 h (100% use of 2*D16 @ 90% MCR)
Station keeping (Dynamic Positioning)	2 h (80% use of 2*D16 @ 90% MCR)
Moored (different tasks)	5 h (70% use of 2*D16, 1*D7 @ 90% MCR)

The workboat is almost always operational on year-basis and is laid-up for maintenance and classification every five years. Therefore, the assumed annual operational profile is based on 354 operational days. The operational profile of a workboat can vary greatly. The reference vessel is designed for an endurance of a maximum of two weeks. The assumed average operational profile is based on 12 h a day and is given in Table VII. The profile is divided into three operational phases: free sailing, station keeping and moored. The table shows the assumed operational characteristics of diesel gensets. The time factor is the relative operational time of the diesel gensets and the load factor is expressed with respect to Maximum Continuous Rating (MCR). In free sailing, two diesel gensets are capable to generate the propulsion power of 750 ekW. In station keeping, both the azimuth thrusters and the bow thruster can be used, requiring slightly less power. In the moored phase the load can be significant, e.g. due to the required power for deck machinery. If necessary, depending on the location and occupation of the ship, the energy demand during the night for Heating Ventilation Air Conditioning (HVAC) can be generated by the small diesel generator (D7).

The benchmark performance including internal costs and external costs is summarised in Table VIII. The upstream (CO_2 equivalent) emissions are based on an emission factor of 43 gCO_2-eq/kWh for (LS) MGO, *DNVGL (2018a), Verbeek et al. (2011)*. The quantified emissions are in the same order as other studies, e.g. *Ammar and Seddiek (2017), Madsen et al. (2011)*. The fuel cost of (LS)MGO (610 €/ton) is based on bunker prices for Rotterdam, https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam. The total annual internal costs (404 k€/y) and the total external costs (307 k€/y) are in the same order of magnitude. It is important to note that the benchmark design is not fulfilling the current regulations for NO_x emissions.

Table VIII: Benchmark performance of the workboat



	B	C	D
51	**Selected energy system**	**HS-4s Diesel (CI) engine (Tier II)**	
52	Predefined fuel		**LSMGO**
53	Energy delivered by energy system [MWh/year]		**3594**
54	Fuel consumption [MWh/year]		**7375**
55	**Internal (investment+operational) costs**		
56	Total investment (equipment+installation) costs [k€]	**k€**	**423.0**
57	Annual investments costs [k€/year]	**k€|y**	**16.9**
58	Operational costs: fuel cost factor [€/ton]	**€|t**	**610**
59	Operational costs: fuel costs [k€/year]	**k€|y**	**379.7**
60	Operational (maintenance) costs [k€/year]	**k€|y**	**7.2**
61	Total operational costs [k€/year]	**k€|y**	**386.9**
62	Total annual internal costs [k€/year]	**k€|y**	**403.8**
63	**External costs of (WTT+TTP) emissions**		
64	**External costs of upstream (WTT) emissions**		
65	E_CO_2-eq [ton/year] & External costs CO_2-eq [k€/year]	**t|y 318.6**	**k€|y 17.2**
66	**External costs of operational (TTP) emissions**		
67	E_NO_x [ton/year] & External costs NO_x [k€/year]	**t|y 15.9**	**k€|y 119.8**
68	E_SO_x [ton/year] & External costs SO_x [k€/year]	**t|y 1.2**	**k€|y 12.0**
69	E_PM [ton/year] & External costs PM [k€/year]	**t|y 1.5**	**k€|y 49.0**
70	E_VOC [ton/year] & External costs VOC [k€/year]	**t|y 0.6**	**k€|y 1.7**
71	E_CO_2 [ton/year] & External costs CO_2 [k€/year]	**t|y 1995.7**	**k€|y 107.8**
72	**Total external costs (WTT+TTP) [k€/year]**		**k€|y 307.4**

The optimisation algorithm has been run using the following settings: the initial population size of 300 and a total number of 40 generations. These values are both much higher than in the electrical ferry case. The more extensive set of relevant abatement options is responsible for this. The output of a genetic algorithm can vary for different optimisation runs. Therefore, the optimisation output with the lowest objective values is selected and the corresponding output data is also noted. First of all, the 11 generated solutions are all feasible. The solution time of this optimisation run was 65.6 seconds and the optimisation converged after 32 generations. The last generation is visualised in Fig.6. This last generation gives a mean distance of 463, a mean objective 1 of 452 [k€/year] and a mean objective 2 of 176 [k€/year]. The figure also shows the benchmark performance in terms of the internal costs and external costs, although this system does not meet the regulations at this moment. The solutions are close to the internal costs of the benchmark because the extra investment costs are offset by lower operational expenses, primarily fuel costs. The objective values of these solutions are studied in more detail below. In Table IX the solution with the lowest internal cost (far left bullet in Fig.6) and the solution with the lowest external costs (far right bullet) are compared with the initial benchmark.

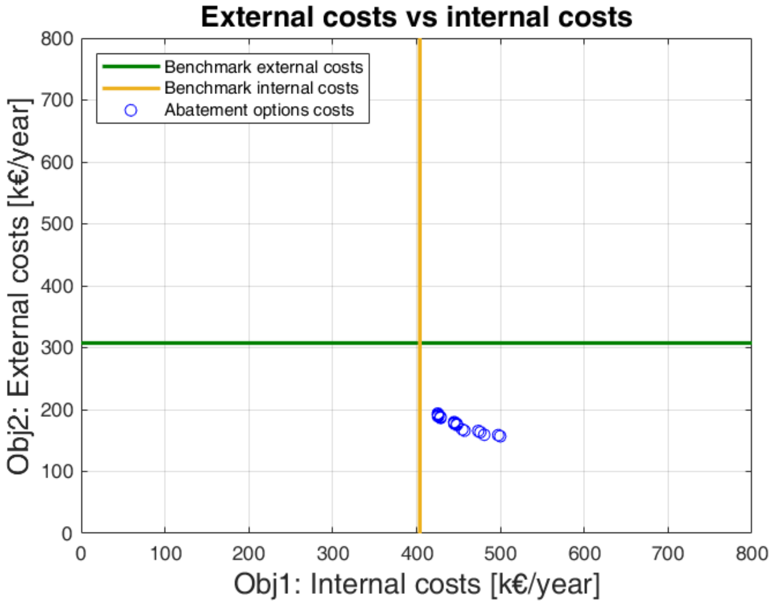


Fig.6: output case study workboat relative to the benchmark

Table IX: Comparison of the optimised solutions with the benchmark for the workboat.

Element	**Benchmark**	**Min. Internal Costs**	**Min. External Costs**
Internal Costs (k€/year)	404	425	500
External Costs (k€/year)	307	194	160
Abatement Options			
System 1		Marine Diesel Oil 0.1%S (MDO)	Marine Gas Oil 0.1%S (LSMGO)
System 2		Selective Catalytic Reduction (fuel <1.5 %S) (SCR)	Fuel Water Emulsification (FWE or WIF)
System 3		Hydrodynamically optimised hull form and appendages.	Selective Catalytic Reduction (fuel <1.5 %S) (SCR)
System 4		Hull coating	Hydrodynamically optimised hull form and appendages.
System 5		Energy-efficient light system	Hull coating
System 6			Propeller optimisation - Higher efficiency, higher URN
System 7			Waste Heat Recovery (WHR)
System 8			Energy-efficient light system

The Selective Catalytic Reduction (SCR) can be found in any combination since SCR is the most suitable abatement option for the high-speed diesel engine to reduce the NO_x emissions to meet IMO Tier III requirements. In both solutions, the hull optimisation, hull coating and energy-efficient lighting are also identified as having positive impacts on the total costs and emissions. MDO as a fuel is much cheaper than the Low Sulphur MGO, hence it is the choice for low internal costs, whereas LSMGO improves the environmental performance a little more. The high-efficiency propeller and Waste Heat

Recovery (WHR) do not deliver enough potential to be earned back economically but can be relevant in stricter owners. The WHR is more suitable for larger ships, as it takes up quite some space. The space availability was not yet considered in this optimisation, on the other hand, a WHR might not even fit on the selected workboat.

Since the benchmark workboat did not meet the legal limits for NO_x it may seem to outperform the optimisation for internal costs. However, the optimisation could be said to identify the impact of the increase from Tier II to Tier III for NO_x regulations. The environmental impact is significant, whereas the operational impact is limited. However, this does assume that, for example, a hull form optimisation was not already performed for the benchmark. It seems unrealistic to expect a further voluntarily reduction by installing extra measures as the impact is limited, and the cost increase significantly. Furthermore, LNG was tested for the benchmark ship as well, resulting in internal costs of 260 k€/year and external costs of 154 k€/year. In both cases, further improvement compared to the presented optimisations. However, there is not enough room to store the LNG and therefore it was excluded from the optimisation. Still, it explains the current popularity of LNG as an abatement fuel, despite the methane slip.

5. Conclusions

The developed selection tool TESTER can select a combination of abatement options taking into account their interactions and optimising for a given set of limits. The potential of TESTER was shown in two case studies, one on an electric road ferry and one for a diesel-electric workboat. In both cases a set of relevant solutions allows the user to study the impact of different combinations of emission abatement options. Also, unconventional or future options and regulations can easily be added to the model to identify the impact of such developments.

A drawback of the current tool is that the space impacts on the ship design are not yet taken into account. It is left up to the designer in the next iteration to further clarify the design of the ship. Of course, once executed the tool could be used again to further select emission and cost reduction options, by manually taking into account e.g. space limitations.

The selection tool TESTER has demonstrated that, as with the MACC approach, sets of solutions can be identified, improving both costs and emissions. These support tools show that there is still significant potential for ship design measures, which perform well both economically and ecologically.

For the future, an integration with a ship design system is planned and an extension or update of the abatement options is crucial to the proper functioning of the selection tool for future ship designs.

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References

ABS (2018), *Guide for the Classification Notation Underwater Noise,* ABS, Houston

AMMAR, N.R.; SEDDIEK, I.S. (2017), *Eco-environmental analysis of ship emission control methods: Case study RO-RO cargo vessel,* Ocean Engineering 137, pp.166-173

AUTHORITY, C.A. (2016), *Standards for offshore helicopter landing areas*, TSO

BALLAND, O.; ERIKSTAD, S. O.; FAGERHOLT, K. (2014), *Concurrent design of vessel machinery system and air emission controls to meet future air emissions regulations*, Ocean engineering 84, pp.283-292

BALLAND, O.; GIRARD, C.; ERIKSTAD, S.O.; FAGERHOLT, K. (2015), *Optimized selection of vessel air emission controls—moving beyond cost-efficiency*, Maritime Policy & Management 42, pp. 362-376

BALLAND, O.; ERIKSTAD, S.O.; FAGERHOLT, K. (2012), *Optimized selection of air emission controls for vessels*, Maritime Policy & Management 39, pp.387-400

BALLAND, O.; SOLEM, S.; HAGEN, A.; ERIKSTAD, S.O. (2010), *A decision support framework for the concurrent selection of multiple air emission controls*, 9th COMPIT Conf., Gubbio

BARI, M.E.; ZIETSMAN, J.; QUADRIFOGLIO, L.; FARZANEH, M. (2011), *Optimal deployment of emissions reduction technologies for construction equipment*, J. Air & Waste Management Association 61**,** pp.611-630

BOLT, E. (2001), *Fast ferry wash measurement and criteria*, FAST'2001 Conf., pp.135-148

BUHAUG, Ø.; CORBETT, J.J.; ENDRESEN, Ø.; EYRING, V.; FABER, J.; HANAYAMA, S.; LEE, D.S.; LEE, D.; LINDSTAD, H.; MARKOWSKA, A.Z. (2009), 2nd IMO GHG Study, IMO, London

BV (2018), Rule Note NR 614 DT R02 E, Underwater Radiated Noise (URN), Bureau Veritas, Paris

CALLEYA, J.; PAWLING, R.; GREIG, A. (2015), *Ship impact model for technical assessment and selection of Carbon dioxide Reducing Technologies (CRTs)*, Ocean Engineering 97, pp.82-89

COMMANDANT, U. (1999), *International regulations for prevention of collisions at sea, 1972 (72 COLREGS)*, US Dept. of Transportation, US Coast Guard, COMMANDANT INSTRUCTION M, 16672

CORBETT, J.J.; CHAPMAN, D. (2006), An environmental decision framework applied to marine engine control technologies, J. Air & Waste Management Association 56, pp.841-851

DAMEN (2020a), *Road ferry 9819*, https://products.damen.com/-/media/Products/Images/Clusters-groups/Ferries/Passenger-Car-Ferry/Road-Ferry/DRFe-9819/Downloads/Product_Sheet_Damen_Road_Ferry_9819_E3.pdf

DAMEN (2020b), *Utility vessel (UV) 4312*, https://products.damen.com/-/media/Products/Images/Clusters-groups/Workboats/Utility-Vessel/UV4312/Documents/Product_Sheet_Damen_Utility_Vessel_4312_01_2017_.pdf

DNVGL (2018a), *Assessment of selected alternative fuels and technologies*, DNV GL Guidance Paper 5

DNVGL (2018b), *Rules for Classification – Ships – Part 6 Additional class notations. Ch. 7,* DNV GL

EEA (2012), *Air Quality in Europe*, European Environmental Agency

EC (2019), *Energy prices and costs in Europe*, European Commission

FELDTMANN, M. (2000), *In the wake of wash restrictions*, RINA Conf. on the Hydrodynamics of High Speed Craft–Wake Wash and Motions Control

GILBERT, P.; WALSH, C.; TRAUT, M.; KESIEME, U.; PAZOUKI, K.; MURPHY, A. (2018), *Assessment of full life-cycle air emissions of alternative shipping fuels*, J. Cleaner Production 172, pp.855-866

GM (2017), *Advancing Environmental Excellence*, Green Marine https://green-marine.org/

HANSSON, J.; MÅNSSON, S.; BRYNOLF, S.; GRAHN, M. (2019), *Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders*, Biomass and Bioenergy 126, pp.159-173

IMO (2004), *International convention for the control and management of ships' ballast water and sediments*, IMO, London

IMO (2014a), *Code on Noise Levels on Board Ships*, IMO, London

IMO (2014b), *Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life*, IMO, London

IMO (2017), *The International Convention for the Prevention of Pollution from Ships*, IMO, London

JOMOPANS (2017), *Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS)* https://northsearegion.eu/jomopans

KIRKEGAARD, J.,;KOFOED-HANSEN, H.; ELFRINK, B. (1999), *Wake wash of high-speed craft in coastal areas*, Coastal Engineering

LR (2018), *ShipRight Design and Construction – Additional Design Procedures: Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise*, Lloyd's Register, London

MADSEN, R.T.; JON, P.; MARKESTAD, L.; DAVID, P.; LARSEN, W. (2011), *144-Car Ferry LNG Fuel Conversion Feasibility Study for Washington State Ferries*, Seattle

McKENNA, M.F.; ROSS, D.; WIGGINS, S.M.; HILDEBRAND, J.A. (2012), *Underwater radiated noise from modern commercial ships*, J. Acoustical Society of America 131, pp.92-103

MEPC (2012), *Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships*, Resolution MEPC 212, IMO, London

MITSON, R. (1995), *Underwater noise of research vessels: review and recommendations*, ICES Cooperative Research Report No. 209

MORO, A.; LONZA, L. (2018), *Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles*, Transport and Environment 64, pp.5-14

MSC (2006), *Adoption of amendments to the international convention to the safety of life at sea, 1974, as amended*, Resolut. MSC 216, IMO, London

MURPHY, J.; MORGAN, G.; POWER, O. (2006), *Literature review on the impacts of boat wash on the heritage of Ireland's inland waterways*, Moore Group

ÖLÇER, A.; BALLINI, F. (2015), *The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation*, Transport and Environment 37, pp.150-170

OSPAR (2017), *OSPAR Commission*, https://www.ospar.org/about/introduction

POV (2017), *Enhancing Cetacean Habitat and Observation (ECHO) Program*, Port of Vancouver https://www.portvancouver.com/environment/water-land-wildlife/echo-program/

RAVEN, H.; VALKHOF, H. (1998), *Ship Wash*, MARIN Report, Wageningen

REN, J.; LÜTZEN, M. (2015), *Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties*, Transport and Environment 40, pp.43-60

RINA (2017), *Amendments to Part A and Part F of the "Rules for the Classification of Ships": New additional class notation: "DOLPHIN QUIET SHIP" and "DOLPHIN TRANSIT SHIP"*, RINA, Genova

SCHINAS, O.; STEFANAKOS, C.N. (2014), *Selecting technologies towards compliance with MARPOL Annex VI: The perspective of operators*, Transport and Environment 28, pp.28-40

TRIVYZA, N.L.; RENTIZELAS, A.; THEOTOKATOS, G. (2018), *A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability*, Energy Conversion and Management 168, pp.128-149

VAKILI, S. (2018), *Under-water noise pollution sources, mitigation measures in commercial vessels: the trade-off analysis in the case of study for trans mountain project*, Port of Vancouver

VERBEEK, R.; KADIJK, G.; VAN MENSCH, P.; WULFFERS, C.; VAN DEN BEEMT, B.; FRAGA, F.; AALBERS, A. (2011), *Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands*, TNO, Delft

WAGNER, C.G. (2005), *Basic combinatorics*, Dept. Math., The University of Tennessee, Knoxville

WANG, H.; FABER, J.; NELISSEN, D.; RUSSELL, B.; ST. AMAND, D. (2010), *Reduction of GHG Emissions from ships–Marginal abatement costs and cost effectiveness of energy efficiency measure*, Document MEPC, IMO, London

WANG, W.; ZMEUREANU, R.; RIVARD, H. (2005), *Applying multi-objective genetic algorithms in green building design optimization*, Building and environment 40, pp.1512-1525

WINEBRAKE, J.J.; CORBETT, J.J.; WANG, C.; FARRELL, A.E.; WOODS, P. (2005), *Optimal fleetwide emissions reductions for passenger ferries: An application of a mixed-integer nonlinear programming model for the new york–new jersey harbor*, J. Air & Waste Management Association 55, pp.458-466

YANG, Z.L.; ZHANG, D.; CAGLAYAN, O.; JENKINSON, I.; BONSALL, S.; WANG, J.; HUANG, M.; YAN, X. (2012), *Selection of techniques for reducing shipping NOx and SOx emissions*, Transport and Environment 17, pp.478-486