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Cost-Emission Relations for Maritime Logistics Support in Aquaculture

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Abstract. This paper presents a method for evaluation of the economic cost of reducing the emissions from a fleet operating in the aquaculture industry. The method accounts for the fact that different fleet compositions perform differently in a given operating environment. A simulation model tests the fleets, returning the achieved mission coverage, total operating cost and emissions. The cost and emissions for each fleet are adjusted for coverage before their relations are analyzed using regression on the Pareto frontier. A case study is performed, estimating the cost of 5%, 10%, 20%, 50% and 100% reductions in CO_2-emissions from well boat operations.

1. Introduction

The main purpose of the aquaculture industry is the farming of aquatic species. Various aquaculture activities such as ocean farming of Atlantic salmon requires the use of vessels to support the production at the sites. Some vessels transport biomass and consumables, others function as work platforms for the execution of operations on the locations. In the case of fish farming well boats carry live fish, delouse fish and sort fish, feed vessels deliver fish feed to the sites, and service vessels perform IMR and other necessary operations. A fleet of vessels serving a set of locations performs the maritime logistics support for that sea-based aquaculture system. The operational performance of the maritime logistics support is determined by its ability to execute the requested operations in the system within reasonable time. Other aspects of the marine logistics support to be considered include safety, fish welfare and pollution, especially greenhouse gas emissions.

Reductions in greenhouse gas emissions are desired in all industries, but to what degree measures are taken depends on the economic consequences. Studies on the effects and selection of measures in the maritime context include [1] and [2]. Measures may also affect the vessel operations e.g. through reductions in cargo space or range. A meaningful comparison of emission reducing measures with respect to cost should therefore consider the effect on the vessel performance. The method presented in this paper tests fleet compositions in a given operating environment and adjusts their total cost and total emissions based on the achieved operational performance.

2. The Method

The basic idea of the method is to compare the operational costs and emissions of a set of fleets which perform equally well with respect to mission demand. Operational costs and emissions are found by simulating the operations of all fleets, in a defined operating environment over a given time period. A flowchart describing the method is shown in Figure 1. A vessel routing heuristic is built in to the simulation model, planning the operations of the vessels for the next planning period, with regular intervals throughout the simulation. In every planning process the heuristic analyses the mission requests from the operating environment and seeks to cover all missions with minimum cost. The aspect of operability of marine operations, both in execution and planning, is inspired by [3], and the work of [4] from the offshore wind industry. While the routing heuristic is based on the ideas presented in [5] and [6].

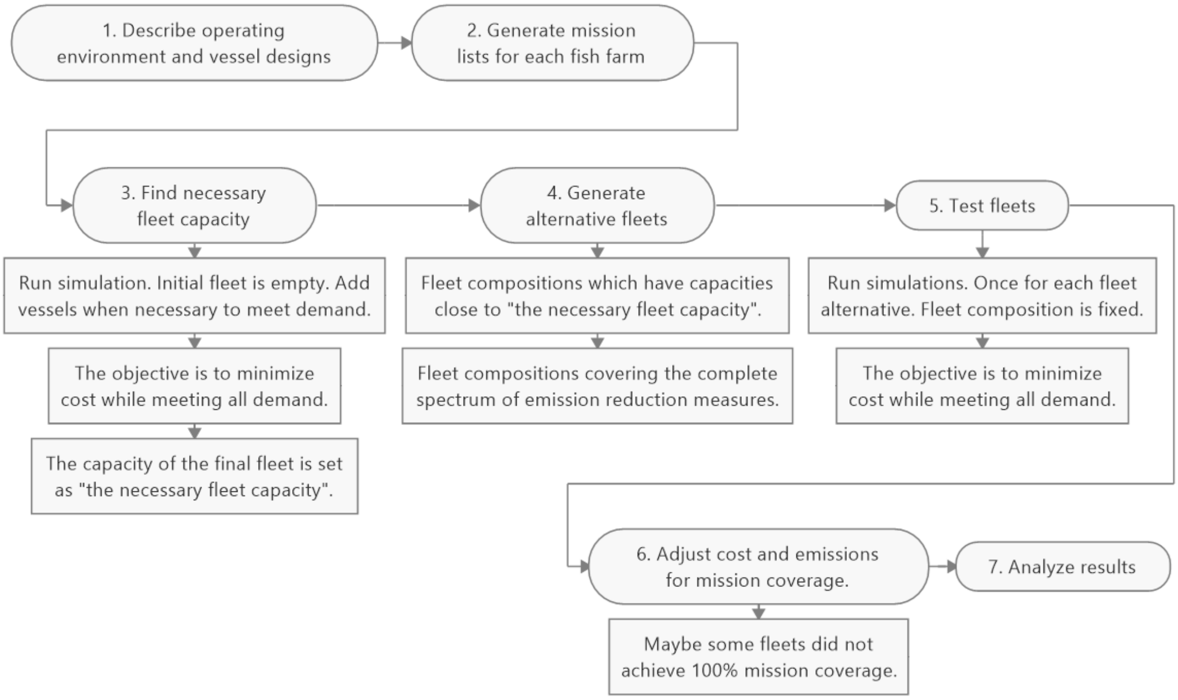

Figure 1. Flowchart describing the main steps of the method.

2.1. Testing fleet compositions

The method can either test for a set of predefined fleets, or for a set of available vessel designs. In the latter case an initial procedure is run, generating alternative fleets with the necessary capacity to cover the mission requests of the operating environment. This capacity is found by running the simulation with a modified version of the routing heuristic. It starts the simulation with an empty fleet and adds vessels to the fleet during each planning process, if it is necessary to cover the requested missions. At the end of the simulation, the heuristic has composed a fleet with enough capacity to cover all requested missions. Having the capacity, alternative fleets are generated randomly from the set of available vessels. However, it is ensured that the generated fleets cover the whole spectrum of available emission reduction measures. That is, some fleets have no measures implemented on any vessel, other fleets have "all" measures implemented on all vessels, while most fleets lie somewhere in between.

All fleets are tested for the same realizations of the stochastic environmental variables to isolate the effect of the differences between the fleets. For each fleet, the achieved mission coverage, total cost and total emissions are returned. Based on the output, the expected total cost and total emissions corresponding to 100% mission coverage are derived for each fleet.

The resulting data set contains an approximation of the cost-emission relation, adjusted for mission coverage, for the set of available vessel designs in the given operating environment. In order to calculate the economic cost of relative reductions in emissions, first the basis fleet must be selected. In a general study of the cost-emission relation, the most cost-efficient fleet is selected as the basis. If all potential fleets have been evaluated, the cost-emission relation is constrained by the resulting data set entries. That is, e.g. interpolation between two entries on the Pareto frontier does not make sense if there are no fleet alternatives populating those areas. However, if the set of possible fleet compositions far outnumbers the tested set, there is a possibility that the Pareto frontier is more densely populated, and thus, interpolation could be defended.

3. The Case Study

The case study covers well boat operations in three cases of different sizes. The purpose of the study is to present an example of the application of the method. The goal of the study is to estimate the relative cost of 5%, 10%, 20%, 50% and 100% reductions in CO_2 emissions from well boat operations.

3.1. Setup, assumptions and simplifications

The three cases differ in the number of fish farms, hatcheries, slaughterhouses and ports, as presented in Table 1. Fish farms are described by the size of the farm, the position and the weather at the location. Size is given by the number of cages and is drawn from a uniform distribution between 4 and 10. All cages are identical and have a capacity of 200 000 fish. Smolt is delivered at 100grams and fish is collected for slaughter at 5kg. The mortality rate is set to 0%, meaning that a cage receiving 20 tons of smolt delivers 1000 tons of fish to slaughter.

Table 1. Case descriptions. The cases are identical with respect to all other aspects than the ones presented here.

Case	Fish farms	Hatcheries	Slaughterhouses	Ports	Area (km^2)
1	10	1	1	2	5 000 (50x100)
2	20	1	2	4	10 000 (50x200)
3	40	2	3	8	20 000 (100x200)

Common for all hatcheries, slaughterhouses and ports is that they have no capacity limitations, both regarding processing and the number of vessels to accommodate at the same time. Hatcheries provide smolt, slaughterhouses receive fully grown fish for slaughter, and ports provide the well boats with any necessary equipment.

Missions are defined by type and scope. The mission types are presented in Table 2 with corresponding operation rates and operational limits for each vessel size (see Table 3). Mission scope is determined by the biomass at the fish farm – all missions cover all biomass. For each farm, a mission list is generated based on distributions for intergeneration times for each mission type, and the causal dependencies between the mission types. First, a time is drawn for the first delivery of smolt, starting the first production cycle, then a time is drawn for the collection of fish for slaughter. During the period between smolt and slaughter, delousing and sorting operations are performed. At the end of the production cycle, after the fish is collected for slaughter, there is a quarantine period before new smolt can be delivered. The scope of the smolt delivery may cover any integer number of cages, from 1 to the number of cages at the fish farm.

Table 2. Vessel sizes, mission types, operation rates and operational limits.

	Small vessels		Medium vessels		Large vessels	
Mission types	Rate (tons/h)	Limit	Rate (tons/h)	Limit	Rate (tons/h)	Limit
Transport smolt	50	2	75	2	100	3
Delousing 1	50	2	75	2	100	2
Delousing 2	200	2	300	3	400	3
Sorting	50	2	75	3	100	3
Transport slaughter	100	2	150	2	200	3

Each fish farm experiences unique weather. Whether a mission can be performed or not depends on the combination of the weather and the relevant operational limit for the vessel in question. In this case study the weather state is described by one parameter ranging from 1 to 5, corresponding to perfect and terrible weather, respectively. An operational limit of 2 means that the vessel can perform the operation in weather state 1 and 2 conditions.

In addition to vessel size (see Table 3), vessels are defined by design speed (see Table 4) and fuel type (see Table 5). Cargo space loss related to lower energy density fuels or more space demanding propulsion systems is not considered in these problem cases, neither is refueling. Choice of design speed and fuel type affect the CAPEX, in terms of relative change from the base vessels presented in Table 3. An increase in vessel design speed requires an increase in installed power, which in turn leads to higher propulsion installation costs and CAPEX. The same argument is made for the choice of fuel type, propulsion systems based on LPG, LNG, Hydrogen and Electricity are assumed to be more expensive to purchase and install than such based on HFO and MDO. These choices also affect cost through fuel consumption, however this expense depends on the energy consumption of the vessel, which is calculated based on the operating states of the vessel. During transit the energy consumption rate is 75% of installed power, 30% while waiting on weather on location and 20% during operations support.

CO_2 emissions are calculated from the energy consumption, using a factor describing the CO_2 production per consumed kWh of fuel, depending on the fuel type (see Table 5).

Table 3. Base vessel types. All vessels in the case study are variations of these base vessels.

Vessel Size	Volume (m^3, tons)	CAPEX ($/day)	Speed (kn)	Power (kW)
Small	1000, 150	2877	10	1000
Medium	2000, 300	4795	11	1450
Large	3000, 450	6712	12	2100

Table 4. Vessel speed variations and the resulting effect on installed power, and therefore also on CAPEX.

ΔSpeed (kn)	ΔPower (%)	ΔCAPEX (%)
-2	-6	-6
-1	-4	-4
0	0	0
+1	6	6
+2	14	14

Table 5. Fuel type variations.

Fuel type	Efficiency (kWh_{output}/kWh_{fuel})	CO_2 (kg/kWh_{fuel})	Price (\$/kWh)	ΔCAPEX (%)
HFO	40%	0.27	0.04	0
MDO	40%	0.25	0.055	0
LPG	40%	0.22	0.085	5
LNG	40%	0.18	0.01	10
Hydrogen	45%	0	0.285	15
Electricity	75%	0	0.20	20

The routing heuristic is set to re-plan vessel assignments every 7 days, and plan for all missions that start within 14 days. A total of 500 alternative fleets are tested for each case, with each test covering 1000 days of operation.

3.2. Results

With 90 available vessel types and relevant fleet compositions having from 4 to 15 vessels, it may be appropriate to assume that there are fleets populating the Pareto frontier that are not tested. Based on this assumption the cost of a relative reduction in CO_2 emissions can be approximated by the intersections between the relevant CO_2 emissions and the Pareto frontier (see Figure 2). For each case, the cost of reductions in CO_2 is found by using the most cost-efficient fleet as the base and using piecewise linear regression on the Pareto frontier. Total cost and total emissions are adjusted by division on the achieved mission coverage.

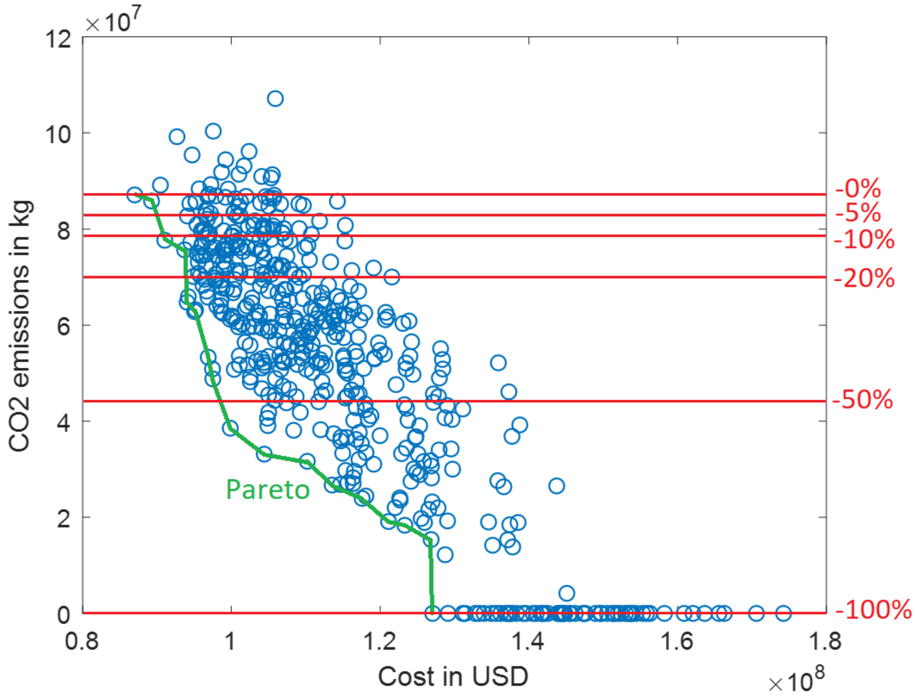

Figure 2. Cost-emission relations for case 3, adjusted for achieved mission coverage. Including stepwise linear regression on Pareto frontier and lines for relative reduction in CO2 emissions.

The costs of the relative reductions in CO_2 emissions for all three cases are presented in Table 6.

Table 6. Analysis results. The cost of relative reductions in CO2 emissions in %-change and absolute change compared to the most cost-efficient fleet composition for each case.

	Cost (Relative, USD)		
Reduction	Case 1	Case 2	Case 3
5%	11.3% , 4.013e+06	14.9% , 1.143e+07	03.4% , 2.930e+06
10%	16.7% , 5.943e+06	15.6% , 1.194e+07	04.5% , 3.880e+06
20%	20.0% , 7.093e+06	16.6% , 1.273e+07	07.9% , 6.900e+06
50%	29.7% , 1.054e+07	36.0% , 2.751e+07	13.5% , 1.171e+07
100%	31.1% , 1.105e+07	39.4% , 3.011e+07	46.1% , 4.011e+07

4. Discussion

As could be expected, the results indicate an increasing cost for greater relative reductions in CO_2 emissions. For Case 1 and Case 2, even a 5% reduction in CO_2 emissions is relatively costly at 11.3% and 14.9% cost increase, respectively. For Case 3, the cost is much lower at 3.4%. From the case study it is hard to identify a general cost-emission relation across the test cases. There is no apparent way of deriving the results of Case 3 based on the results of the two other cases and the known differences between the cases. This finding supports the hypothesis that a simulation-based approach is beneficial for studying these relations.

A potential source for error is the assumption on the position and shape of the Pareto frontier. While the assumption of more fleets populating the Pareto frontier is supported by the high number of untested fleets, the certainty of the position of the Pareto frontier is not. However, the clustering of the tested fleets in Figure 2 may indicate that it is unlikely that the true frontier is substantially different from the test results.

Other sources of error related directly to the execution of the case study relate to the simplifications made in defining the operating environment, the vessels and their operations. An example is the calculation of energy consumption and CO_2 emissions not considering that machinery efficiency and CO_2 production depends on machinery load. Another example is that cargo space loss related to the choice of fuel type is not included, however this can be included by changing the vessel designs included in the case. Despite the simplifications, it could be argued that the effect is limited because the case study compares the fleets rather than seeking to identify the exact performance of a single fleet. As such, if the simplifications have a similar impact on all tested fleets, the effect on the final result may be insignificant.

The model allows for other emission reduction measures to be included, provided that the measures can be described in terms of the parameters of Table 3, Table 4 or Table 5. A better hull shape, improved propeller design or a more fuel-efficient propulsion system running on the same fuel type, are examples of such measures that can be included. In terms of the vessel parameters, the effect will be increased CAPEX, reduced power demand and increased efficiency. Further, the model allows for inspection of the cost utility of different measures. The results of all fleets are logged making it possible to see what measures were implemented by which fleets. This way the effect of e.g. speed reductions on cost and emission can be isolated by identifying otherwise similar fleets with changes in design speed.

The presented method could aid authorities and business in their work towards making the industry greener. It is indicative in quantifying the cost of proposed reductions in greenhouse gas emissions, enabling both policy makers and businesses to make the right decisions based on a broader assessment.

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