



Effective utilization of service vessels in fish farming: fleet design considering the characteristics of the locations

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Received: 18 November 2021 / Accepted: 2 September 2022
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Abstract

Effective utilization of service vessels in sea-based fish farming requires that the vessels are suited to the operating environments at the fish farms. This paper presents a methodology for assessing service vessel fleet performance when serving a network of farms with different metocean conditions. Fleet performance is defined as the ability to perform operations requested by the fish farms, in due time. An optimization for simulation approach is employed, implementing a routing and scheduling heuristic developed for aquaculture service vessels. A case study was performed assessing the performance of two different fleets serving a set of 21 fish farms. The variation in local metocean conditions between the farms, and how weather changes in time, challenges the operability of the aquaculture infrastructure and the effective routing and scheduling of the vessels. Hence, the results show that proper fleet composition in this context improves fleet performance. Fleet performance is substantially higher when fleet composition, routing, and scheduling is based on the specific weather conditions.

Keywords Sea-based fish farming · Weather exposure level · Location environment · Fleet performance · Routing and scheduling · Simulation

Introduction

Sea-based farming of Atlantic salmon has seen almost a sevenfold increase in production volumes in Norway from 1998 to 2020 (Norwegian Directorate of Fisheries, 2021a). Ever larger cages have been installed at new locations, often with higher weather exposure. With the introduction of the development license scheme in Norway (Norwegian Directorate of

Handling Editor: Gavin Burnell.

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Fisheries, 2021b), the industry started a transition towards more exposed locations with even larger cages and infrastructure resembling offshore structures from oil and gas (Bjelland et al., 2016; Nordlaks Produkter AS 2021; Norway Royal Salmon ASA, 2020; Nova Sea AS 2021; SalMar ASA 2020). Expansion into new areas, especially areas with challenging weather conditions, involves a site selection process including multi-criteria evaluations considering environmental, economic, and social aspects (Chahinez et al., 2020; Dapuzeto et al., 2015; Pérez et al., 2005). The effect of the environment on the fish, and the effect of the production on the environment, is extensively studied in the literature (Dunne et al., 2021; Frankic & Hershner, 2003; Holmer, 2010; Hvas et al., 2020). However, how the environment affects the operation of fish farms, and in particular the vessel operations, is less studied. Sea-based fish farms are geographically spread and have different metocean conditions, which result in differences in the environmental loads at the farms (see Fig. 1). This covers both the simultaneous weather and the long-term statistics. Even for fish farms that are close to each other, the local geography can affect the weather to the extent that there is little correlation between the weather at the farms. A given set of fish farms are supported by a specific fleet of vessels with various designs that have different capabilities and seakeeping abilities. Vessel operations are performed if the weather conditions at the location are acceptable. Overall performance of a set of fish farms is dependent on the capability of the fleet of vessels to perform vessel operations at the farms given the weather at the locations.

Full utilization of the service vessel feet is only achieved if the vessel fleet routing, scheduling, and deployment is optimal, and able to consider the stochastic nature of operation requests from the farms and the weather at the locations. This entails that the operation of the service vessel fleet is not a question of making the right or wrong decisions, but it is an optimization problem weighing operating costs against operational performance (Lianes et al., 2021).

The interaction between vessel and fish farm infrastructure, and how it is affected by weather is studied in detail (Shen et al., 2019b, 2019a; Shen et al., 2018a; Shen, Greco, Faltinsen, et al., 2018b). Operational performance of single vessels in terms of operability

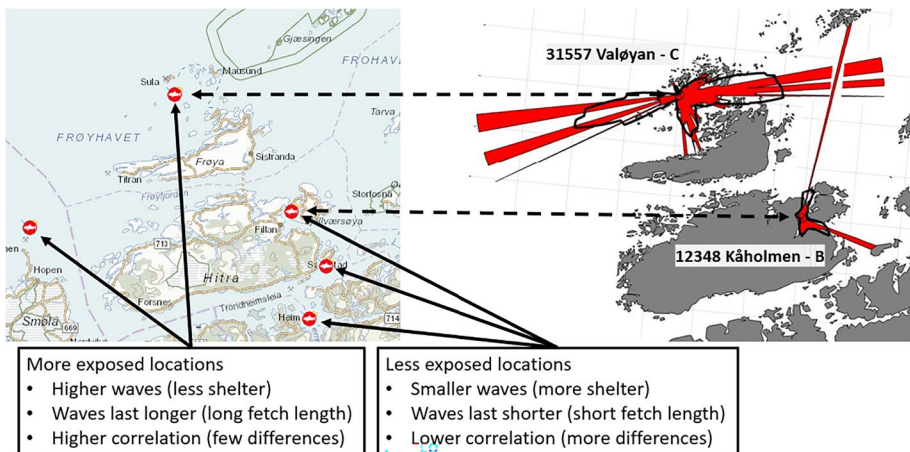


Fig. 1 A summary of typical differences between less and more exposed fish farms. The right-hand side illustrates fetch lengths for the Valøyen and Kåholmen locations. That is, how waves can build up before reaching the farm. Left-hand map is retrieved from the Norwegian Directorate of Fisheries (2021a)

is studied for other maritime industries, including percent operability based on scatter analysis (Gutsch et al., 2016; Tezdogan et al., 2014), the relative rate of operation based on discrete-event simulation (Sandvik et al., 2018), and the operability robustness index (Gutsch et al., 2020). For other segments, such as traditional shipping, the literature also covers long-term operational performance of fleets of vessels in the context of strategic problems such as the maritime fleet size and mix problem (Álvarez et al., 2011; Pantuso et al., 2014; Sperstad et al., 2017), and short-term maritime fleet routing and scheduling (Álvarez, 2009; Lianes et al., 2021; Psaraftis, 2019).

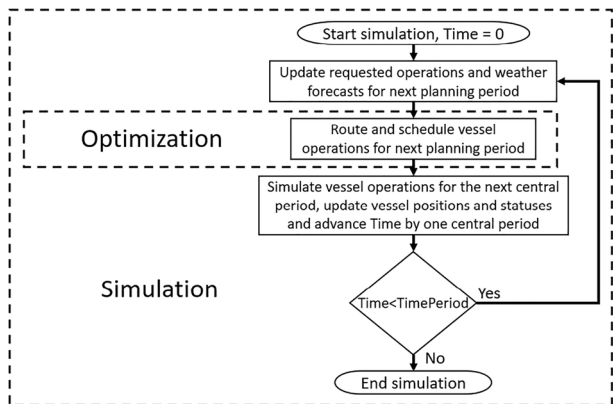
The research question of this paper is how weather conditions affect service vessel fleet performance in sea-based fish farming. In answering this question the paper contributes to the literature by (1) establishing a method for assessing the effects on fleet performance and (2) quantifying the effect on the fleet performance from selected variations in weather conditions. Assessment of service vessel fleet performance is methodologically based on an operations research approach adapting a rolling horizon framework employing optimization for simulation. The methodology is developed to enable scenario testing.

Materials and method

The solution method is based on testing the fleet performance for different fleets and weather scenarios, and then analyzing the variations in performance. Testing of a single fleet and weather scenario is performed by simulating operation of the fleet for a given time period, serving a set of fish farms according to their requests for vessel operations. Fleet performance is defined as the portion of the requested operations that the service vessel fleet manages to perform within the given time windows. A weather scenario is a time series of the weather at each considered fish farm covering the complete chosen time period. Optimization for simulation (Fu, 2002) is applied, with discrete event simulation, in a rolling horizon framework where new information on weather forecasts and requested operations are revealed at fixed intervals (Fagerholt et al., 2010; Fu, 2002) (see Fig. 2). The heuristic of Lianes et al. (2021) optimizes routing and scheduling of the vessels.

Every time the sub-problem is solved, the total period of the rolling horizon is divided into four; the fixed, central, forecast and far future periods (see Fig. 3). The fixed period covers what has already happened, the central and forecast periods together make up the

Fig. 2 A flow chart of the optimization for simulation procedure with rolling horizon. Optimized routing and scheduling for vessel operations are generated at fixed intervals for the complete duration of the rolling horizon



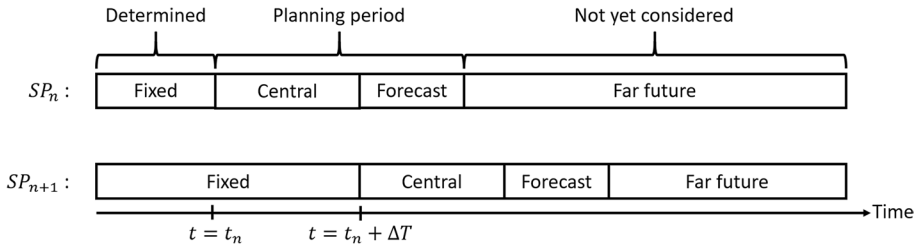


Fig. 3 The relation between the periods in a rolling horizon. Inspired by (Brevik et al., 2020). Sub-problem n (SP_n) is solved at time $t = t_n$, while sub-problem $n + 1$ (SP_{n+1}) is solved at time $t = t_n + \Delta T$, where ΔT is a fixed duration

planning period which is the period the sub-problem is solved for. Finally, the far future period covers the future beyond what is considered in the sub-problem. Sub-problem $n + 1$ (SP_{n+1}) is solved at the end of the central period of sub-problem n (SP_n) (see Fig. 3). The reason that the planning period is longer than the central period is to avoid solving it in a way that is disadvantageous to the long-term objective. Furthermore, the length of both the central period and the forecast period is a compromise between computational time and solution quality (Andersson et al., 2015; Stolletz & Zamorano, 2014).

The behavior of the service vessel fleet is simulated for the duration of the central period after solving a sub-problem. When solving SP_{n+1} , the resulting vessel positions and statuses from the simulation that followed the solution of SP_n is used as initial vessel positions and statuses. The objective function of the sub-problem is to maximize the number of completed operations, considering all operations as equally important and disregarding costs. This is a modification from the objective function used in Lianes et al. (2021) where a more realistic system of profits and costs is used, and where the various operations are given different priorities. The modification of the objective function to only return one parameter, is made to minimize ambiguity in the comparison of the fleet performance of the different fleets and weather scenarios. For details on the heuristic solving the routing and scheduling sub-problem, see Lianes et al. (2021).

Design of experiments

A case study assesses how the performance of two different fleets of service vessels change for different weather scenarios, and the length of the operation time windows. First, the details of the studied system are presented before the different weather scenarios and time window lengths are described. An experiment is one combination of vessel fleet composition, weather scenario and time window length.

The studied system: a system of fish farms of varying exposure level

The study covers 21 sea-based fish farms off the Norwegian coast (see Fig. 4). The shortest sailing distance between any two farms is less than 1 nautical mile and the longest is approximately 58 nautical miles. All the fish farms are assumed to be identical with respect to size and technical solutions, having a total capacity of 3120 tons each and consisting of flexible, open net pens.

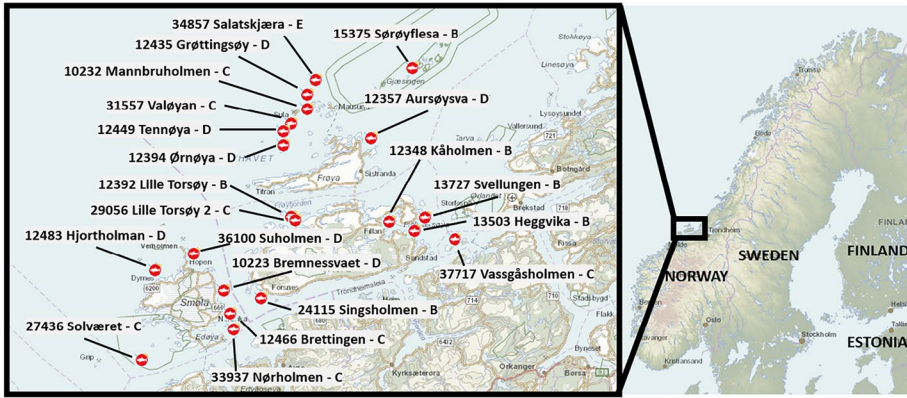


Fig. 4 Number, name, and wave class of the 21 considered fish farms off the mid-west coast of Norway. Maps are retrieved from the Norwegian Directorate of Fisheries (2021a)

In Fig. 4, the number, name, and wave class of each fish farm is presented, with the latter being based on the 1-year significant wave height (H_{s1year}) and wave peak period (T_p) (see Table 1). There are five wave class levels according to a definition in the appendix of Standards Norway (2009), ranging from A “Low exposure” to E “Massive exposure.” The wave class of the fish farms are based on 16-year wind wave time series generated using fetch analysis (Lader et al., 2017). Fetch analysis is using the distance from the farm to nearest land in the various directions to analyze the build-up of waves. It is worth noting that the fish farms in the study cover the range from “Moderate exposure” to “Massive exposure,” and that most fish farms have “Large exposure” or higher.

At each fish farm the time between two consecutive requests for the same operation type is exponentially distributed with a mean of 14 days. Vessel operations are only performed if the wave height does not exceed the operational limit of 0.5 m. This entails that the wave height is the only weather parameter considered in the study. The limit is chosen based on the practice at a specific fish farm, according to conversations with the personnel at the farm. However, it should be noted that in practice the exact limit is not strictly enforced due to the variations and inaccuracy in the subjective perception of the weather.

The duration of the operations is 4 h, which means that a weather window of at least 4 h is needed to perform an operation. A weather window is a period of consecutive sea states that do not exceed the operational limit (Det Norske Veritas AS 2011). Operations are usually required to be performed within some reasonable time relative to the time of the request, often referred to as the time window of the operation. This is the period within

Table 1 Wave class definitions for 1-year significant wave height (H_{s1year}) and peak period (T_p), borrowed from the appendix of Standards Norway (2009). Translated from Norwegian

Wave class	$H_{s1year}[m]$	$T_p[s]$	Designation
A	0.0 – 0.5	0.0 – 2.0	Low exposure
B	0.5 – 1.0	1.6 – 3.2	Moderate exposure
C	1.0 – 2.0	2.5 – 5.1	Large exposure
D	2.0 – 3.0	4.0 – 6.7	High exposure
E	> 3.0	5.3 – 18.0	Massive exposure

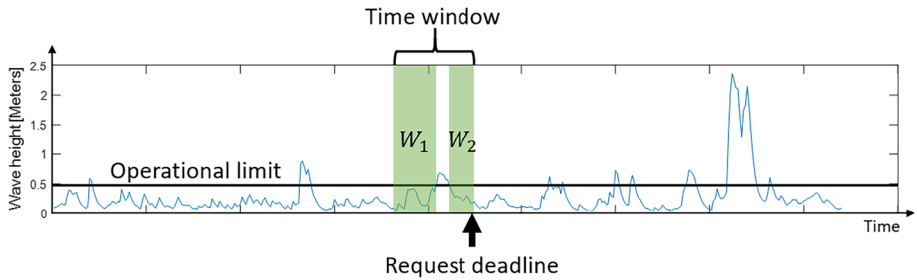


Fig. 5 Illustration of how weather windows (W_1 and W_2) are found based on time window, operational limit and weather condition. The time window describes a period within which the operation can be started, and the operational limit and weather further restrict possible starting times

Table 2 Overview of the considered vessel types, including what operations they can perform and their designation

Vessel type	Can perform operation type	Vessel designation type
1	1, 2, 3	Multi-purpose
2	1	Specialized
3	2	Specialized
4	3	Specialized

which the operation can be initiated, and it ends at the time of the request (see Fig. 5). Three different time window lengths are tested in the study: 3, 6, and 9 days.

Four vessel types are included in the study, composing two different fleets:

- One homogeneous fleet of multi-purpose vessels.
- One heterogeneous fleet of specialized vessels.

The homogeneous fleet consists only of vessels of type 1, while the heterogeneous fleet consists of vessels of types 2, 3, and 4 (see Table 2). Three operation types are considered, referred to as types 1, 2, and 3, and they differ only in terms of the required functionality a vessel must have to perform them. Vessel type 1, the multi-purpose vessel, can perform all three operation types, while vessel types 2, 3, and 4 are only able to perform one each: operation types 1, 2, and 3, respectively.

Weather scenario variations

A 16-year wind wave time series generated for each fish farm by Lader et al. (2017) is the basis for the weather scenarios used in the experiments. The time series consists of 6-h sea states, which means that the weather is the same for 6 h at the time.

This paper investigates the effects of three ways in which the weather scenarios can vary. Variation 1 is change in exposure level, which corresponds to change in the average wave height. Variation 2 is change in continuity, which corresponds to change in how the wave height is distributed in time. Finally, variation 3 is change in correlation, which is the correlation in wave height between the fish farms. The variations are chosen because they cover important aspects of the differences between sheltered and exposed fish farms (see Fig. 1).

Higher waves are expected when moving further offshore, longer fetch lengths means that the sea takes longer to calm, and the correlation between the farms is higher for exposed farms because there are fewer geographical elements creating local conditions.

Variation 1: change in exposure level

Weather scenarios at the fish farms are changed by multiplying all sea states in the time series with a factor, either increasing all wave heights or reducing them. Three exposure level modifiers are introduced: low, medium, and high. Low corresponds to a reduction of the wave class of each location by one step, and the high corresponds to an increase of one step. That is, in the low modification a location which has “Large exposure” according to the original wind wave time series is changed so that it has “Moderate exposure” instead. This is achieved by multiplying each element of the time series with a constant corresponding to the relation between the two wave classes according to the definition in Table 1. In the case of going from “Large exposure” to “Moderate exposure,” the factor is 0.5. The same logic is applied when increasing the wave heights to get the high exposure level modification. The medium modification entails no such change to the wave height time series. Figure 6 shows the three modifications for the Bremnessvaet fish farm, where the middle graph is the wave height time series with the medium modification. Bremnessvaet has “High exposure” originally, meaning that low modification gives “Large exposure,” and high modification gives “Massive exposure.” These are the lower and upper graphs in Fig. 6, respectively.

Variation 2: change in continuity

Continuity describes to what degree waves build up and accumulate, according to the relation in Eq. 1. The wave height in the i th sea state, H_i , is a function of the wind waves of the same sea state, H_i^w , and the wave height in the previous sea state, H_{i-1} . This means that the wave height in a 6-h period is a function of the waves in the previous 6-h period and the waves made from the wind in the current 6-h period. The continuity, C in Eq. 1, is a number between 0 and 1 determining the portion of the wave energy that is carried over from the previous sea state. A higher C -value results in waves taking longer to dissipate, and the waves being higher on average.

$$H_i = \sqrt{H_i^w{}^2 + CH_{i-1}{}^2} \tag{1}$$

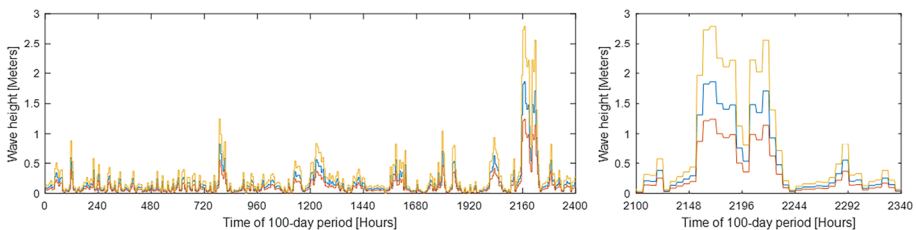


Fig. 6 Illustrating exposure level modification of a 100-day sample of wave height at Bremnessvaet. The middle line is the medium modification, while the lower and upper lines are low and high, respectively

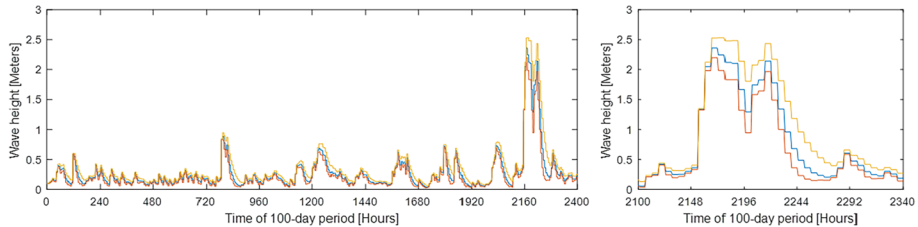


Fig. 7 Illustrating continuity levels for a 100-day sample of wave height at Bremnessvaet. The lower, middle and upper graphs have 35%, 50%, and 65% continuity, respectively. All three have medium exposure level modification

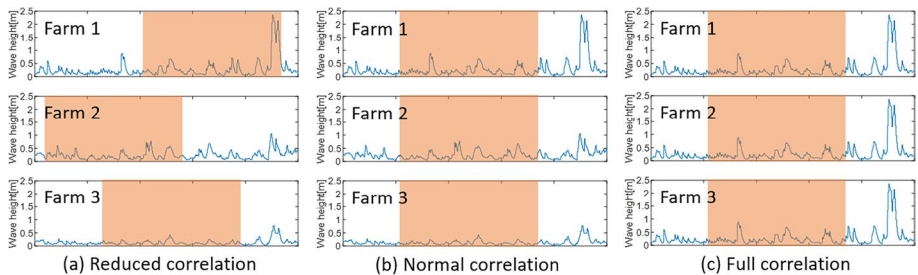


Fig. 8 Illustrating differences between correlation levels. Fish farms experience the highlighted period of the time series. For reduced correlation the farms experience different periods from different time series, while for normal correlation the farms experience the same period from different time series. Full correlation gives the exact same weather to all locations

Three levels of continuity are studied: 35%, 50%, and 65%. All fish farms share the same continuity level in each case. This is a significant simplification with respect to the real-world behavior where the extent to which a wave state affects the next depends on several factors such as the local geography, the magnitude and direction of the former wave state, and the magnitude and direction of the current waves (Holthuijsen, 2007). However, this coarse approximation does give the desired modification to the wave height time series, as seen in Fig. 7 where the 35%, 50%, and 65% continuity levels of Bremnessvaet are presented for the medium exposure level modification. Comparing the graphs to the middle line of Fig. 6, which has 0% continuity, the waves are higher, and they take longer to dissipate. This is amplified for higher continuity levels, resulting in longer “tails.”

Variation 3: change in correlation

The waves at the fish farms are somewhat correlated because all the farms lie within a relatively small area. However, the waves are also affected by local conditions that differ for each fish farm. The three correlation levels considered in the study are reduced, normal and full correlation, with normal correlation being the actual correlation between the fish farms. This means using samples of the time series from the same time period for all the fish farms (see Fig. 8 (b)). The reduced correlation level selects samples for the fish farms from different periods (see Fig. 8 (a)). The full correlation level uses the exact same weather for all fish (see Fig. 8 (c)).

Experiment design summary

Table 3 presents a summary of the parameters that are varied in the case study. An experiment is defined by the levels for the different parameters, giving a total of 162 possible experiments while the weather scenarios are based on the exposure level modification, continuity level and correlation level, giving a total of 27 different weather scenarios. Each experiment is simulated for a 100-day period, with a 3-day central period and a 2-day forecast period. Each experiment is tested for five different realizations of operation requests, and the average performance is presented as the result for the experiment.

Results

Variations in weather scenarios among the fish farms affect fleet performance. Magnitude and specifics of the effects depend on fleet composition and length of time windows. First, the performance of the two different fleets is presented for changes in weather scenarios. Then, the performances of the same fleets are given for variations in time window lengths, for a selection of weather scenarios. Finally, fleet performance is described for different fleet sizes. The multi-purpose fleet (MP) consists of three vessels of vessel type 1, and the specialized fleet (SPZD) consists of three vessels, one of vessel type 2, one of type 3, and one of type 4.

Varying weather scenarios

The multi-purpose fleet performs better than the specialized fleet for all weather scenarios. Figure 9 presents the results for 3-day time windows, and all considered variations in weather conditions. The results are consistent in that higher exposure level modification or increased continuity always gives a reduction in performance. Negative effects on performance seems to be amplified between continuity and exposure level. That is, effect of changes in continuity are larger for larger exposure level modification, and effect of changes in exposure level modification is larger for higher continuity.

Higher correlation is not necessarily negative as both fleets, in most cases, perform better with normal correlation than reduced correlation. On the other hand, there is a significant reduction in performance for full correlation.

Table 3 Explanation of the parameters that are varied between the experiments. Levels (modifiers) describe what values the parameters can take

Parameter	Description	Levels (modifiers)
Exposure level	1-year significant wave height	Low, medium, high
Continuity	Energy carry-over from previous sea state	35%, 50%, 65%
Correlation	Similarity in wave height development	Reduced, Normal, Full
Time window length	Period within which an operation can be initiated	3, 6, 9 days
Fleet composition	The only vessel type in the fleet	Multi-purpose, specialized

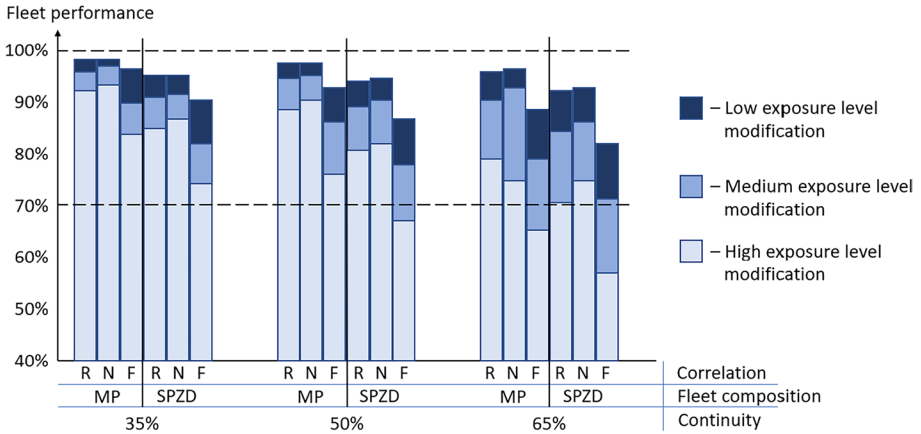


Fig. 9 Achieved fleet performance for 3-day time windows and variations in correlation, fleet composition, continuity, and exposure level modification. R, N, and F designate reduced, normal, and full correlation, respectively. For fleet composition, MP means multi-purpose and SPZD means specialized. Both the multi-purpose and specialized fleets consist of three vessels each. Bars in darker shades are placed behind the ones in lighter shade, and are thus taller

Varying time window length

Longer time windows improve fleet performance, and the effect is larger for high exposure level modification and full correlation (see Fig. 10). In addition, the specialized fleet seems to be slightly more sensitive to variations in time window durations than the multi-purpose fleet. Changes in time windows give approximately the same absolute effects for all three levels of continuity, across other weather characteristics and fleet composition.

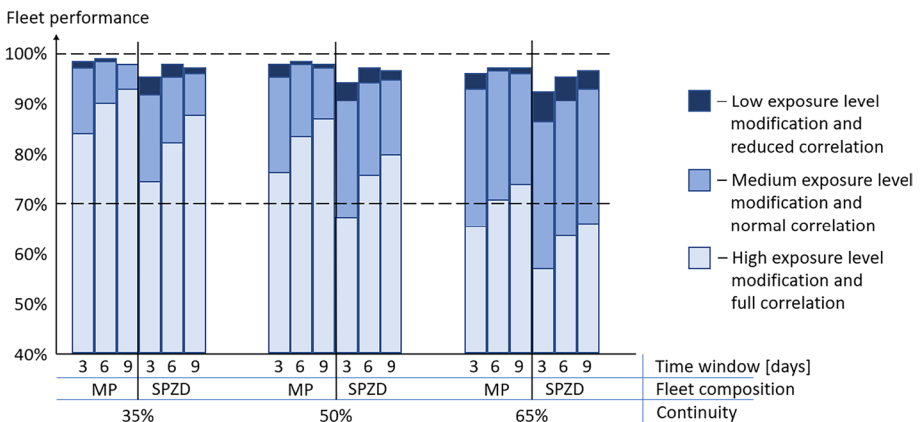


Fig. 10 Achieved fleet performance for selected combinations of exposure level modification and correlation, and for all combinations of time window duration, fleet composition and continuity. For fleet composition, MP means multi-purpose and SPZD means specialized. Both the multi-purpose and specialized fleets consist of three vessels each. Bars in darker shades are placed behind the ones in lighter shade, and are thus taller

That is, e.g., increasing the time window duration from 6 to 9 days yields the same percentage point increase in performance for the lightest shade, 35%, MP-bars as for the lightest shade, 65%, MP-bars. Longer time windows can to some degree compensate for change in continuity. For 35% continuity longer time windows can almost compensate for increased exposure level modification and correlation.

Varying fleet size

More vessels will never have a negative impact on fleet performance. However, the marginal contribution of each extra vessel decreases rapidly and seems to converge. Figure 11 presents the fleet performance of fleets of multi-purpose vessels, with fleet size ranging from 1 to 8 vessels. The results are shown for three selected scenarios with respect to weather and time window duration. When weather effects are ignored, a fleet performance of 100% is achieved for a fleet of four vessels. In the two other scenarios weather conditions are challenging, and time windows of 9 and 3 days yields fleet performances of 96.6% and 82.2%, respectively, for a fleet size of eight. The gap between the lightest and darkest shade describes the effect of shorter, fewer, and coincident weather windows between the fish farms.

Discussion

The relevance of the presented method is based on the expansion of the sea-based fish farming industry into more exposed waters which both introduces more challenging weather conditions for vessel operations and an increased spread in simultaneous weather between fish farms, from sheltered to fully exposed locations. This expansion entails uncertainty about how well current solutions perform. Important questions cover if fish farms should

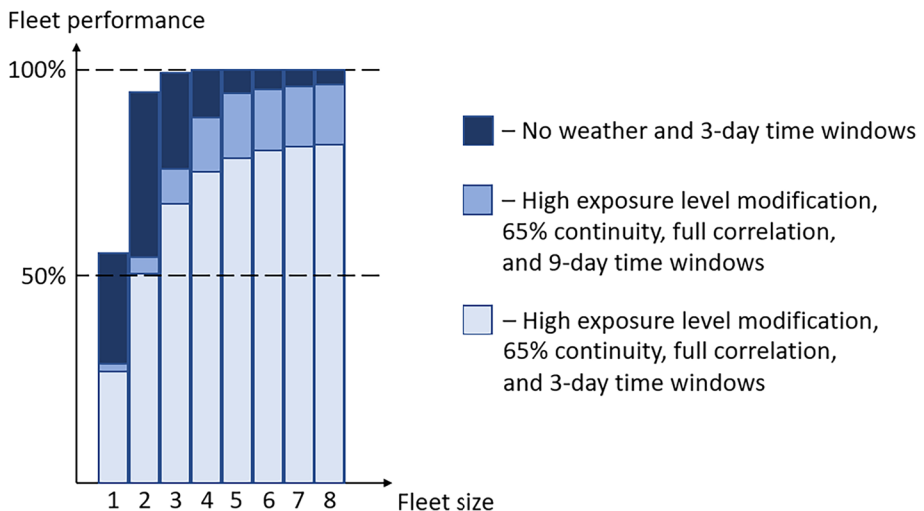


Fig. 11 Achieved fleet performance for different sized fleets of multi-purpose vessels. The results are presented for three selected weather scenarios, indicated by the different shades of color

be divided into groups based on exposure that are operated by dedicated fleets of vessels, if and what new technological solutions that are needed to enable operation at exposed locations, how to best compose fleets of service vessels to serve a number of fish farms experiencing very different weather, and if any other measures can be taken to improve fleet performance. A method enabling the assessment of fleet performance through scenario analysis is a valuable tool for getting answers to such questions and providing insight to support decision processes.

The presented method achieves this by performing short-term simulations of the operation of the fleet, including specific mission lists and weather time series and a flexibility in changing fleet composition and fish farms during the simulations. This means that all possible system configurations can be tested, and absolute fleet performance can be retrieved. However, for a given scenario the accuracy of the fleet performance depends on the match between the vessel routing method used in practice and the method applied in this paper. Perfect validity is achieved if the routing and scheduling in the method is the same as the one used for the real-world situation of the considered fleet, and if the considered weather scenarios and operation request are perfect representations of the behavior of the real system. The idea behind the chosen setup of the method is that comparing the maximum performance of the fleets is a valid approach for comparing fleet alternatives and that fish farmers seek optimal utilization of the vessels they operate. Most vessels in fish farming are either routed individually or not routed using optimization methods, meaning that the performance established by the method is likely to be higher than that of the real-case scenario. Scenario testing also complicates extreme event testing because it is not readily given what weather and mission list scenarios that give the lowest fleet performance, that is, establishing extreme event scenarios with respect to weather and mission lists may not give the “desired” extreme event scenarios for fleet performance.

The method for solving the operational sub-problems is based on the routing heuristic of Lianes et al. (2021), an Adaptive Large Neighborhood Search (ALNS) heuristic tailored for solving the problem of routing service vessels in sea-based fish farming considering several of the most important characteristics of the routing problem such as operational limits, time windows, functional requirements, heterogeneous fleets and prerequisites for performing operations. Configuring the method requires the selection of a range of parameters including the duration of the central and forecast period and parameters related to solving the sub-problem such as the number of search iterations, randomness in the search, and the profits and costs. Most parameters of the ALNS heuristic were kept unchanged compared to the configuration used in Lianes et al. (2021), except for the number of search iterations which was reduced to give a shorter computational time, and the profits and costs which were changed to simply maximize the number of completed operations. That is, all operations were given the same profit and all costs were set to zero. A sensitivity analysis was performed to investigate the reduction in solution quality from the implemented reduction in the number of search iterations, and it was found to be within a couple percent of the absolute performance and not affecting the ranking order of the experiments.

Weather scenarios and vessel characteristics are based on real data that are modified to perform the desired experiments. For the weather, this entails creating time series with somewhat exaggerated characteristics such as the full correlation, but that are well suited to demonstrate the direction and magnitude of effects from changes in weather scenarios. Even though the construction of the modified time series can be questioned, the resulting time series are judged reasonable and show the desired variation for the experiments. Only a limited number of experiments were performed, but they do provide a demonstration of the variations in fleet performance that can result from different weather scenarios. It

should also be noted that only one parameter is used to represent weather, and even though significant wave height is often the main consideration with respect to operational limits for vessel operations (Det Norske Veritas AS 2011), other parameters like wave period, wind, and current are also important (Sandvik et al., 2018; Shen et al., 2019b). Vessel characteristics are not extensively described in the method, only including sailing speed, what operations the vessels can perform, and operational limit. Having a common operational limit for the three operations and two vessel types does not necessarily decrease the validity of the experiments as there are several examples of this being the case in practice, either because many vessels have similar motion characteristics or because they have similar interactions with the fish farm.

Testing the fleet performance of two different fleets for a range of different weather scenarios is in line with the purpose of the method and provides insight on the potential effects of changes in weather scenarios on fleet performance. The tested weather scenarios are relevant for the expansion of the industry into more exposed locations, and the changes in time window length and the two fleet compositions cover a variation in fleet design and measures to improve fleet performance.

As expected, the results show that higher exposure level modification reduces the fleet performance and that the multi-purpose fleet performs better than the specialized fleet. The latter is supported by the higher utilization of the multi-purpose vessels because they, on average, need to sail shorter between operations when optimally routed, and they consequently achieve a superior utilization of the weather windows of the operations on a fleet level. Higher continuity and correlation both give reductions in fleet performance similar in magnitude to that of higher exposure levels, using the definition of the terms and the level values presented in this paper. Interestingly, the effects seem to follow the superposition principle, in terms of how the effects add to a total percentage reduction. Exposure level and continuity affects how often the locations are unavailable for vessel operations and for how long each time. Full correlation poses a challenge for locations where periods of rough weather are frequently expected, because it can lead to a spike in vessel operation demand as soon as the weather calms. As such, full correlation requires better operation planning to avoid a build-up of the vessel operation backlog, than for low or normal correlation where the availability of the locations is more evenly spread, which in turn reduces the peak demand. For high correlation, having a high peak demand in comparison to the capacity of the fleet of service vessels results in additional delays for vessel operations at fish farms after becoming available again after periods of rough weather. The largest difference in performance for a fleet in the case study is almost 50% between the least and most challenging weather scenarios, for the specialized fleet with three vessels.

Increasing the time window lengths and the number of vessels in the fleet both improves fleet performance, with the time windows determining the upper boundary the fleet performance approaches with increasing size (see the convergence in Fig. 11). The results therefore show that it is possible to serve a set of farms of different exposure with the same fleet of vessels and still achieve high fleet performance. Increasing the number of vessels, and the time window lengths can, in the case of the fleet of multi-purpose vessels, bring the performance back up close to 100%. However, 100% fleet performance requires additional measures such as higher operational limits, more vessels in the fleet, and designing fish farms and planning their operations so that it is not necessary to perform vessel operations in rough weather. The latter does not cover emergency operations which, by definition, cannot be planned for and must therefore be addressed through the other means.

Using the presented method to perform scenario analyses can improve decision making on vessel procurement and how to organize and deploy vessels based on the weather

conditions at the locations. Scenario analysis can also be used operationally to study the effectivity of different response actions in shorter periods of challenging weather or testing possible operational changes for improvement of day-to-day operation. In addition, the method can provide insight on the effect of possible challenging situations or disrupting event and changes, and the effectivity of the available tools for dealing with such situations. Improved insight is likely to give higher fleet performance which in turn affects operation costs. Requested operations are usually necessary for the operation of the fish farms which means that the fish farmers desire a fleet performance of 100% and are interested in the most effective ways of approaching such high performance. The worst-case scenario is that insufficient fleet performance leads to operational difficulties at the fish farms, which in turn can result in reduced fish welfare and reduced profitability.

The results indicate that all considered parameter variations in the experiment setup do have significant effect on fleet performance and should therefore be assessed when composing service vessel fleets and determining what fish farms the various vessels serve. A main finding is that vessels should be organized so that they share responsibility of farms that are not fully correlated. It is also clear that higher exposure levels and higher continuity reduces performance. However, the fact that the industry is expanding to more exposed locations is mainly driven by the scarcity of sheltered locations, hence it is not a solution to avoid rough conditions all together.

This method opens for evaluating vessels' ability to cooperate, and how that is affected by different operating conditions, e.g., weather conditions and time windows. Significant reductions in performance, like what was seen in Fig. 10, would indicate a need to reevaluate the fleet composition. Considering actual time windows and operational limits, the fleet performance should ideally be close to 100% depending on the acceptable level of spot charter. Even though special purpose vessels are on the rise, decision makers should consider the value of procuring versatile vessel designs so that they can perform other operations if that is beneficial for the total performance. E.g., modular vessel designs.

Figure 11 shows that increasing the fleet size is not always a solution, which also means that improved sailing speed or operational durations do not solve the problem if weather windows are too few or coincident. Then, the only solution is higher operational limits.

With new farm concepts and new vessel designs being introduced, experience-based knowledge is less relevant and methods for objectively assessing complex relations are necessary.

Conclusion

This paper presents a method for assessing the performance of a fleet of aquaculture service vessels serving a set of fish farms at locations of varying exposure level under diverse weather conditions. The motivation is the expansion of sea-based fish farms into more exposed areas, and how this sets new requirements for vessel operations on the fleet level to support the fish farms. A case study demonstrates changes in fleet performance for different weather scenarios, fleet composition, and time windows for operations. Exposure level, continuity, and correlation, as defined in the paper, all have significant impact on fleet performance, giving a total reduction in performance of almost 50% in the most severe scenario in the case study. More vessels and longer time windows can, in the case of a fleet of multi-purpose vessels, bring the performance back up close to 100%. The studied locations cover existing fish farms, and with a future increase in the number of exposed locations and

diversity in designs and technical solutions, the benefit of performing fleet performance assessments is likely to only increase. Scenario analyses can be a powerful tool for decision support both for short-term routing problems and long-term fleet composition and fish farm design.

Acknowledgements The authors would like to thank Professor Pål Furset Lader for providing the fetch length mappings for the locations 31557 Valøy and 12348 Kåholmen.

Author contribution Conception and design were mainly the works of Hans Tobias Slette and Bjørn Egil Asbjørnslett. Material preparation, data collection, and analysis were performed by Hans Tobias Slette, Bjørn Egil Asbjørnslett, and Kjetil Fagerholt. The first draft of the manuscript was written by Hans Tobias Slette, and Bjørn Egil Asbjørnslett and Kjetil Fagerholt commented on previous versions of the manuscript. Ingeborg Margrete Lianes, Maren Theisen Noreng, and Hans Tobias Slette have developed new software used in the paper. All authors read and approved the final manuscript.

Funding Open access funding provided by NTNU Norwegian University of Science and Technology (incl St. Olavs Hospital - Trondheim University Hospital) This research has been funded by the Research Council Norway, EXPOSED Aquaculture Research Centre, grant number 237790. The funding source had no influence on the research or the preparation of the article.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability The code generated in the current study is available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Competing interests The authors declare no competing interests.

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