Deliverable 4.4
Final model for fish behaviour

Version 1.0

WP 4
Deliverable 4.4
Lead Beneficiary: Sintef Ocean
Call identifier: Biological and Medical Sciences - Advanced Communities: Research infrastructures in aquaculture
Topic: INFRAIA-01-2018-2019
Grant Agreement No: 871108
Dissemination level: PU
Date: 30.09.2024

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871108 (AQUAEXCEL3.0). This output reflects only the author's view and the European Commission cannot be held responsible for any use that may be made of the information contained therein.

Contents

1. Objective

The purpose of this report is to present an individual based fish behaviour model for simulating full-scale fish populations in cages and tanks. This model is one of the main components in the Virtual Laboratory that is being developed in Task 4.1 of the AQUAEXCEL3.0 project. The Virtual Laboratory also includes components on growth, water quality and flow fields, and the behaviour model has been designed to provide and retrieve relevant information to and from these components.

The objective of the behaviour model is to assist users in designing experiments in aquaculture research facilities by simulating fish population behaviour for different experimental setups.

In order to give an overview of available functions and limitations of the model, we give an overview of the original fish behaviour model, new model development, software implementation, integration in the Virtual Laboratory and to the other models, introduction to how to use the model as well as challenges experienced and choices made during the development.

2. Background

This report is part of AQUAEXCEL3.0 WP4/Joint Research Activity 1 - *Technological tools for improved experimental procedures*. Task 4.1 - *Virtual Laboratories and modelling tools for designing experiments in aquaculture research facilities* aims to extend the Virtual Laboratory developed in AQUAEXCEL2020 as a general tool for designing and simulating virtual complex experiments in advance of a trial by: 1) adding a new model of fish behaviour, 2) expanding the growth model and applying it to new species, 3) improving the flow model, 4) expanding the water quality model to include CO2 and pond systems, and 5) enhancing the user experience by improving decision support through an Artificial Agent.

The objective of Subtask 4.1.2 is to further develop an individual-based fish behaviour model for simulating full-scale fish populations (e.g., 200 000 fish) in open sea cages and closed tanks. It is based on the further development of an existing model for salmon behaviour in open net cages such that it can be applied to other TNA-infrastructures and species (e.g., European Seabass), provided that sufficient data are available for parameterising relevant behavioural responses in the existing model formulation.

The original behaviour model has previously been implemented in SINTEF Ocean's in-house software for time-domain simulations of marine structures and systems, FhSim[1] (Reite et al., 2014, Su et al., 2019). Testing, further development and implementation of new functionality and validation have therefore been conducted in FhSim. Changes to the model and new implementations has been performed on top of the existing model in FhSim (used as project background). In the following, the main aspects of the original behaviour model will be briefly presented. The further development of the behaviour model, both in AQUAEXCEL 3.0 and in other projects, will be outlined in section 3.1.

[1] https://fhsimweb-public-marine-ict-public-web-public-2f4666754b0a0ef8e4.pages.sintef.no/

The existing fish behaviour model in FhSim for Atlantic salmon was closely based on the model presented by Føre et al., (2009). One of the main goals with this model, according to Føre et al., (2009), was to simulate vertical swimming behaviour. The original behaviour model considers different factors or parameters that affect the fish swimming behaviour. They are the cage limits or boundaries including the water surface, which is static, and three dynamic parameters, which are feeding, temperature and light. Temperature and light will only vary vertically in the model. The fish will also try to avoid colliding with each other, which is modelled through defining a preferred range of distance to neighbouring fish and having a set of rules to decide how the fish will react dependent on how close the fish is to other individuals. The fish behaviour model does not model any reaction to variations in salinity and oxygen levels.

3. Methodology

3.1. Original behaviour model and development in other projects

The fish behaviour model is a result of further development of an existing fish behaviour model (Føre et al., 2009) which was implemented in the software FhSim. The model in FhSim has been further developed in this and parallel projects through modifications and added functionality where necessary in order to meet development goals. The original model (Føre et al., 2009) is an individual Lagrangian based model, which means that each individual's swimming behaviour is modelled. This means that each fish's response, e.g. swimming velocity and direction, to different environmental factors are calculated. Consequently, the simulated position of each fish in the production volume is known and group responses for the population can be found.

3.1.1. Reaction to a moving boundary – cage walls and bottom

In the original model (Føre et al., 2009) the cage walls and bottom were static. In the current model the deformation and position of the net cage walls and bottom is calculated by a structural model (implemented in project RACE BIORACER). The position of the various parts of the cage walls and bottom is affected by factors such as water current, waves, dimensions of the net cage and the weight that is applied to the net cage in order to reduce the deformations that may occur in current and waves (Su et al., 2019, 2023). In the present model, the fish behaviour model is using the updated positions of the netting, thus the behaviour model is able to simulate how the fish may react to changes in the production volume due to net deformations (applicable for flexible sea cages subjected to water current and waves). See Figure 1 for a screenshot from FhSim simulating a fish population in a deformable net cage.

3.1.2. Reaction to current

The fish model takes water current velocity into account when simulating the fish response. This makes it possible to simulate fish behaviour in environments where there is movement of the water. This means that both water current (see Figure 1 and Figure 2) in the sea and flow fields in tanks, where water inlets and outlets (water pumped in and out of the tank) sets up a velocity field, may affect the fish. The new development and implementation of the model in FhSim enables space-varying fluid velocity vectors for current (albeit constant in time). This is important as it enables simulation of the swimming behaviour of fish in fish tanks with complex fluid velocity fields. The inclusion of these complex flow fields requires flow field velocity data from e.g. an external software (see section 3.2.3).

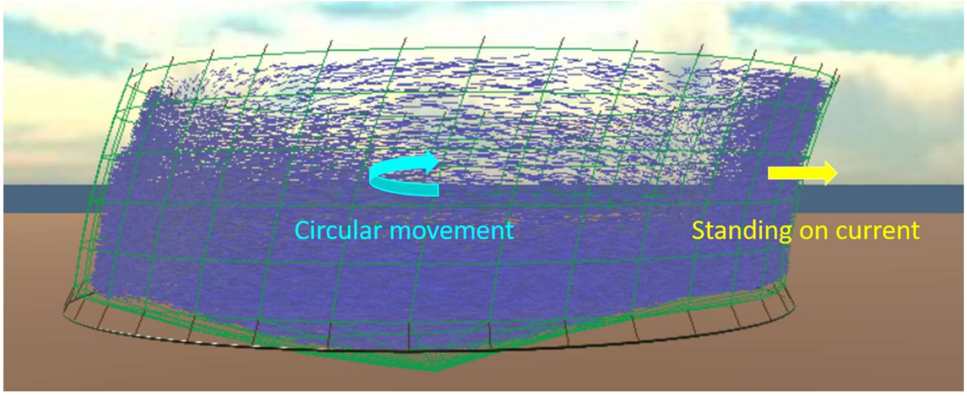


Figure 1: Fish population in water current. Development and figure from RACE BIORACER.

When the fish are dragged by the flow and approaching enclosure boundaries, it is assumed that they would move towards the upstream side (i.e., from where the prevailing water currents are coming) in order to avoid collisions with the enclosure. This effect has been implemented in combination with fish behavioural responses to enclosure boundaries and other individuals. Figure 1 and Figure 2 show the shift from the typical circular movement of salmon in sea cages to stationary swimming against the water currents, which is in accordance with field observations when different current velocities were present (Johansson et al., 2014). The development and implementation were done in the project RACE BIORACER.

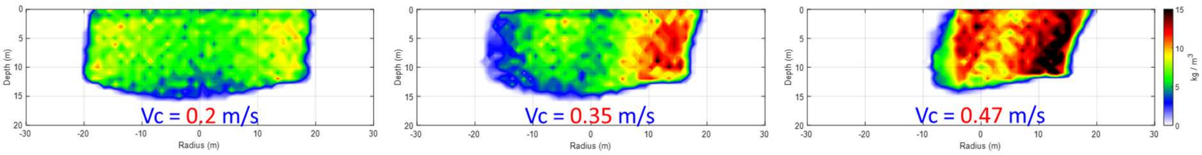


Figure 2: Colour plots of simulated fish density in a cage in water current. Vc is the current velocity in m/s, while the colours in the figure indicates fish density in kg/m^3 according to the colour bar on the right hand side. Development and figure from RACE BIORACER

3.1.3. Reaction to waves

Waves result in movement of the water that is different from water current or the flow fields in tanks. In waves the velocity is changing with time. The magnitudes of the circular motions of the water and corresponding accelerations depend on the wave heights and wave periods. The effect of long waves reaches deeper than the effect of short waves. A simple avoidance criterion has been applied for fish to move downwards from the depths where the water particle velocities and accelerations are higher than a threshold value (Klebert et al., 2023). As shown in Figure 3 and Figure 4, the simulation model is able to reproduce the observed fish distributions in currents and waves, i.e., farmed salmon actively chose to move towards the upstream side of the sea cage and avoid the surface when high waves are present (Johannesen et al., 2022). The development and implementation were done in the projects FlexAqua, SFI EXPOSED and RACE Welfare.

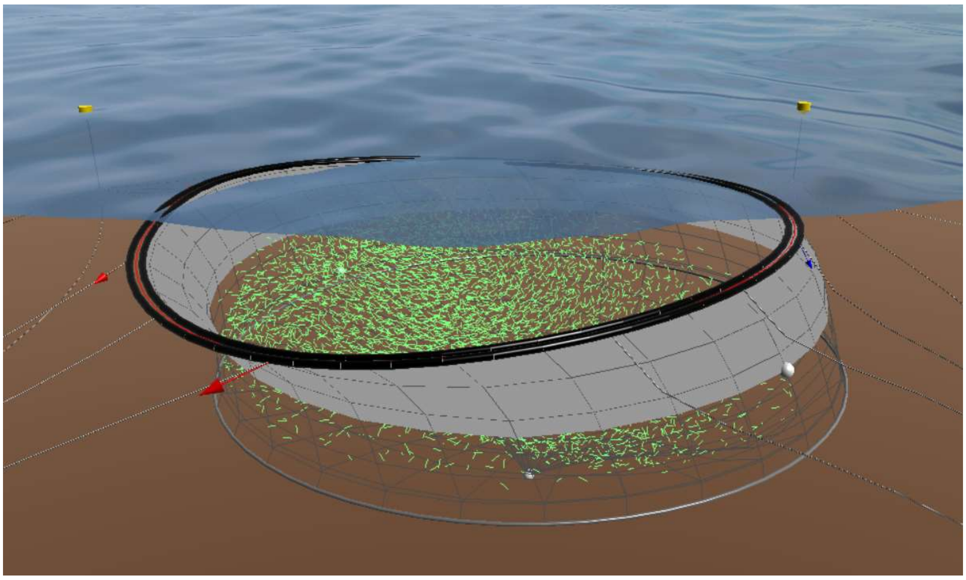


Figure 3: Screenshot from FhSim of a simulation of a fish population in a cage in waves. Development and figure from FlexAqua, SFI EXPOSED and RACE Welfare

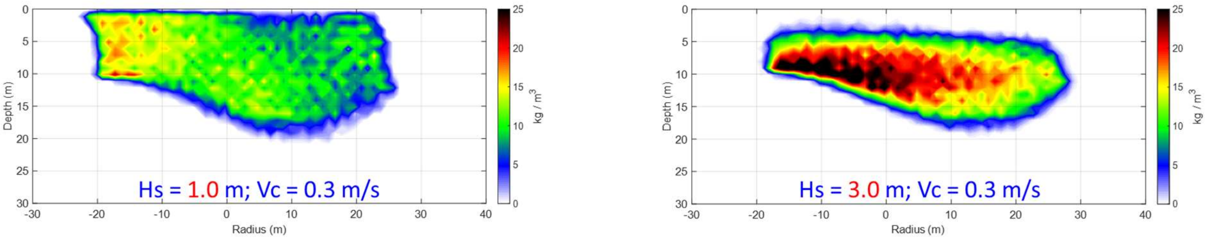


Figure 4: Colour plots of fish density in a net cage as simulated by FhSim in waves and current. Vc is the current velocity in m/s and Hs is the significant wave height in m. The colours in the figure indicates fish density in kg/m^3 according to the colour bar on the right hand side. Development and figure from FlexAqua, SFI EXPOSED and RACE Welfare

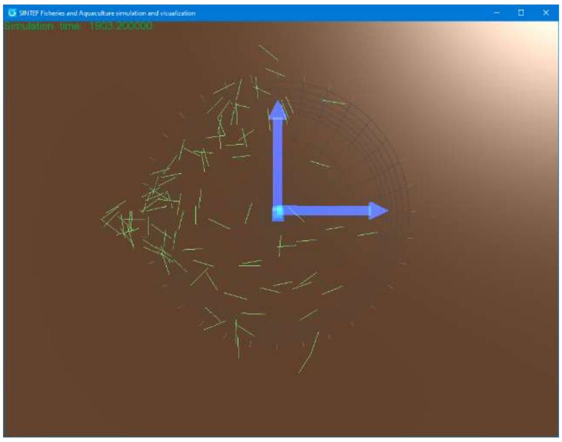
3.1.4. Super individual

The fish population in a single commercial fish cage in Norway can be as high as 200 000 individuals (farming of Atlantic Salmon). An objective is to be able to simulate 200 000 individuals in a net cage in real-time. With real-time it is meant that the time it takes to simulate an event is similar to the duration of that event in real time. This is not easy to achieve, and it depends on the capabilities of the computer hardware in addition to the methods and algorithms employed. When there are requirements of simulation speed trade-offs between accuracy or detailed modelling, and simulation efficiency and speed may be necessary. It is for instance important that the model accuracy is adequate for the application and purpose of the model. To be able to efficiently simulate 200 000 fish one instance of an individual was modified to be able to approximate the total behaviour response of several individuals. The super-individual concept (Scheffer et al., 1995), which allows zooming from a real individual-by-individual model to a cohort representation without changing the model formulation, has been applied for real-time simulations of full-scale fish populations in sea cages and relevant digital twin implementations (Su et al., 2023). The development and implementation were performed in the project RACE DigitalCage.

3.2. Model development in Aqua Excel 3.0

3.2.1. Adapting the model for tanks

The original model implemented in FhSim was adapted for sea based net cages, which means that the methods originally were adapted for and validated with simulations of fish populations in cages with a certain size (Føre et al., 2013). In theory, the model can simulate fish behaviour in smaller enclosures, such as small land-based tanks for Atlantic salmon. Føre et al. (2018) used a modified version of the model presented in Føre et al. (2009, 2013, 2016) to simulate fish populations in tanks in order to estimate growth performance. Initial testing of how the present fish behaviour model implementation in FhSim performed for simulation of fish swimming behaviour in smaller enclosures revealed that the fish were crossing the enclosure boundaries (the tank walls), which means that the modelling or implementation of the models of how the fish avoids the cage walls where not functioning according to the intentions (see Figure 5, simulation of swimming behaviour in a circular tank with a 5 m diameter).



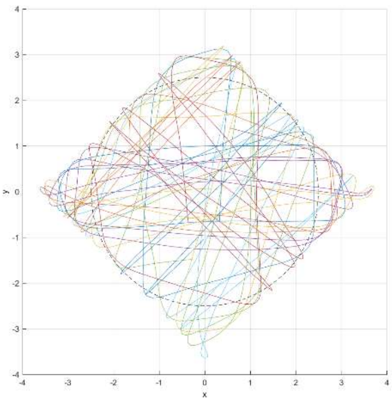


Figure 5: Screenshot from simulation of a fish population in FhSim in a 5 m diameter circular cylindrical tank (Left) and plot of swimming traces (paths) derived from the FhSim simulation for selected individuals (right). The trace is plotted in Matlab. These figures are an example of simulation results before modifications to the algorithm detecting the closest wall boundary was conducted. The circular tank boundary can be seen as a dotted circle in the figure to the left.

In the original implementation of the behaviour model in FhSim, the algorithm responsible for modelling the fish trying to avoid the cage walls were dependent on receiving the dynamic position of the nearest part of the net cage (or tank) walls. The implementation (in FhSim) of the behaviour model seeks to simulate the fish behaviour efficiently. This means that the design of the algorithms also tries to reduce the amount of CPU time (time needed for calculations) that is needed. Finding the dynamic position of the cage walls may constitute large computational costs as each fish may need to seek through many or all enclosure boundary elements in order to find the nearest one. As the number of fish one wants to simulate increase, the computational time needed to evaluate each fish's distance to the boundaries in order to calculate the appropriate response may increase rapidly. An algorithm was previously implemented to mitigate this challenge. The algorithm identifies the nearest boundary elements based on the position of the fish and connectivity matrices, and calculates the normal distance to the identified element, avoiding searching through all the elements. For small enclosures comparable to small tanks, it was found that this method was not reliably able to identify the correct part of the enclosure that the fish was closest too. The results of this were that the modelled fish was not able to stay within the boundaries of the simulated tank (see Figure 5).

As realistic modelling of behaviour is important to understand the fish response as well as providing e.g. the growth model with realistic values for swimming speeds, average feed ingestion etc., efforts were made to enable more realistic modelling of fish behaviour in small tanks. Since the fish population in tanks is much smaller than the population in sea based cages the need for efficient simulation - although still important - is not as acute as for when simulating the fish population in full scale commercial sea cages. Therefore, a brute force approach to identify the closest boundary to each fish for each time step was chosen. The method involves searching through and finding the normal distances from the fish to all wall elements in the model for the enclosure. The normal distance is the shortest distance from the fish to the plane of an element. The element that has the smallest normal distance to the fish is then chosen as the closest element. This is done for each fish in the simulated population for each time step in the simulation, and thus will lead to increased computational costs. However, this method is robust (for circular tanks) and proved during testing to identify the correct parts (elements) in the vertical walls of a circular fish tank.

The original fish behaviour model and iterations have been validated against trials with fish in sea cages (Føre et al., 2016), but the validation of the behaviour in small tanks is limited to the authors knowledge. However, Espmark et al. (2017) conducted and evaluated experiments on smolt and post-smolts reared in different sized tanks in order to evaluate how tank size and change in tank size affected the fish. Although not the primary focus, the study monitored the swimming activity with video cameras and noted that the fish in the larger tanks showed larger variation in their swimming behaviour than the fish in the smaller tanks. Further, the fish varied between holding their position by swimming against the current, drifting backwards or active swimming. Føre et al. (2018) used the behaviour and growth model presented in Føre et al. (2009, 2013, 2016) to estimate growth performance in different sized tanks and compare the results to experiments presented in Espmark et al. (2017), thus indirectly testing the behaviour model against experiment data for tanks. A major difference from the original formulations of the behaviour model is the inclusion of effect of water velocity on fish swimming behaviour and the feed pellet distribution (original feed model presented in Alver et al. (2004, 2016). This was added to be able to include the effect of flow patterns usually seen in tanks used for rearing of fish. The velocity field then affected the calculation of swimming behaviour as well as the calculation of pellet distribution.

3.2.2. Feed distribution model for tanks

Modelling the feed distribution may be important as it may affect the fish feeding and swimming behaviour. The feed distribution model implementation in FhSim is similar to and based upon the 3D feed pellet distribution model presented by Alver et al. (2016) – of which the first version of the model was introduced for 2D pellet distribution in Alver et al., (2004). Føre et al. (2016) also used the feed distribution model from Alver et al. (2016) to model growth performance and feeding behaviour when testing the performance of the model against full scale experiments. The pellet distribution model includes modelling of the feed spread at the surface, pellet sinking speed, diffusion and effect of water current. For modelling of fish behaviour in tanks the feed pellet distribution, or rather the method of adding feed pellets to the simulation environment, needed to be modified. Instead of being distributed on the surface according to a feed spreader model, the feed pellets in the tank implementation are distributed evenly across the water surface of the tank (although this may not be entirely realistic). The amount, duration and when feeding is activated can be adjusted through simulation input parameters. The feed pellets are affected by the fluid velocities in the tank. The feed distribution model involves using a cubic grid of cells. In a circular tank some of these will be outside the tank. The effect of this is sought mitigated by only adding feed to the surface cells which centre is inside the radius of the tank. On average and as an estimation this will provide feed to the cells that is within the tank volume. In addition, the modelled fish are prevented from swimming outside the tank, meaning it can only access the feed in grid cells which are within a given distance. Having a sufficient number of grid cells will mitigate and reduce the effect of adding feed to cells partly outside the tank volume. It is also thought that the cells which centre is outside the tank volume while a part of the cells is inside also will mitigate this. The feed will "fall out" of the production or tank volume at the bottom until it is removed from the simulation when it falls beneath the lowest grid cells. This means that the model is not able to simulate e.g. feed accumulation on the bottom of a tank. However, it may be that it is practically removed from the consideration when it "falls" out of the bottom as the fish when being a certain distance away from the feed is no longer able to access it, since the modelled fish is prevented from crossing the bottom boundary. The number of grid cells vertically can be adjusted in simulation input such that the exceedance beneath the tank bottom is reduced.

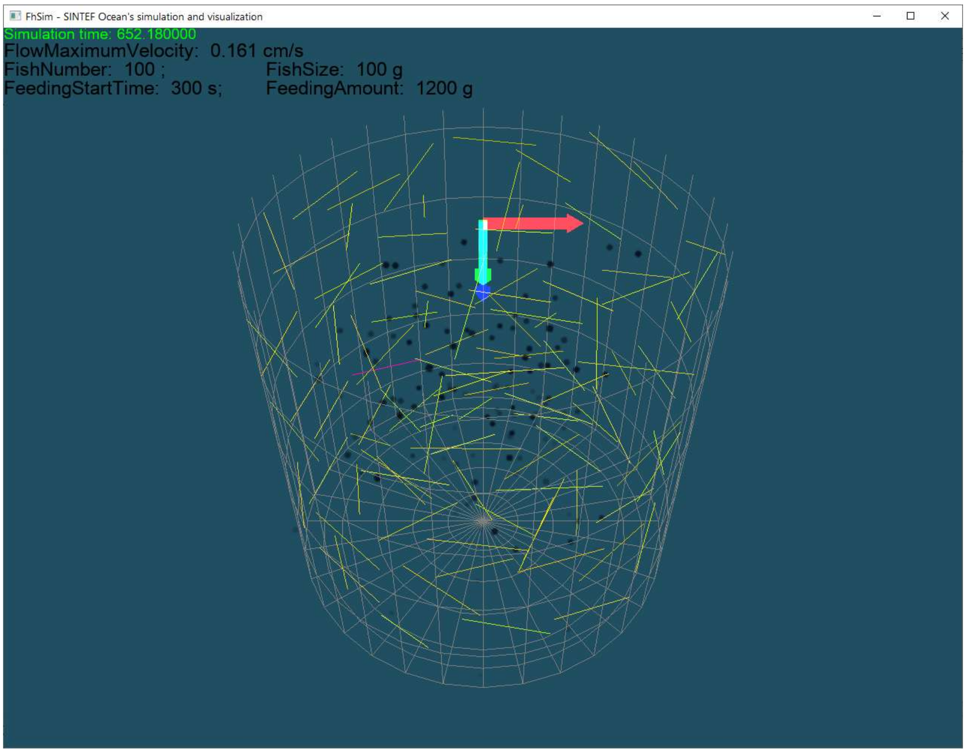


Figure 6: Screenshot of a simulation (FhSim) of 100 fish with a mean weight of 100 g in a 1 m diameter tank. The tank boundaries can be seen as a circular grid while fish are visualized as lines of various colours, depending on the hunger and ingestion status of each fish. The feed, visualized as a black hazy dots, can be seen to stay within the tank volume laterally but fall out of the tank volume vertically. Note that the feed pellet visualization does not accurately depict neither the correct amount or distribution and density of pellets in the volume as there is inconsistencies in the visualization method.

3.2.3. Coupling the model with the flow model

A tank for rearing of fish usually has a system for regular exchange of the water in order for wastes to be removed and fresh water supplied. This system usually consists of inlets and outlets supplying or removing water from the tank. This will induce water movement and thus a flow field in the tank. This will, dependent on velocity magnitudes, affect the fish and be important to model. Not only will the flow field affect how often the water in the tank is exchanged with fresh water, it may also affect how the fish swim and use energy. Being able to add the flow field in a tank to the Atlantic salmon behaviour model is therefore important for modelling of swimming behaviour in tanks. In task 4.1.3 the flow field in tanks for rearing of fish is investigated. Calculating the flow field, meaning for instance fluid velocities in the fluid volume, may be challenging and require specialized software. For flow in for instance tanks with inlets and outlets Computational Fluid Dynamics (CFD) methods can be used to calculate the potentially complex flow field inside a tank. The flow fields calculated in task 4.1.3 where constant in time but varied in the spatial coordinate. This means that the velocity magnitude and direction is constant in time for a given position, but may vary if one move to another position in the tank. Using CFD software require expertise and time. For instance, preparing the simulation with discretization of the fluid volume, setting the correct boundary conditions and performing the simulations require human resources and time, and a simulation may require CPU time in the magnitude of hours or even days dependent on the complexity of the simulation. This means that a co-simulation of for instance a CFD model and the fish behaviour model may not be reasonable to attempt. Instead, the work focused on how the results from task 4.1.3 could be utilized in the behaviour model. Code from task 4.1.3 was incorporated in a FhSim Dynamic Library (DLL) in order to make results from 4.1.3 available to the behaviour model. When FhSim needs the fluid velocity vector for a position, function calls ask for the velocity at the given position. The code (from task 4.1.3) extracts and interprets the information from a NetCDF file containing flow field information from a CFD simulation in order to provide FhSim with the flow velocity vectors. An example of FhSim accessing flow velocity information from a NetCDF file in a simulation of fish behaviour in a tank is shown in Figure 7. The red arrows in the figure show both the direction of the flow at different positions in the tank as well as the velocity magnitude (arrow length).

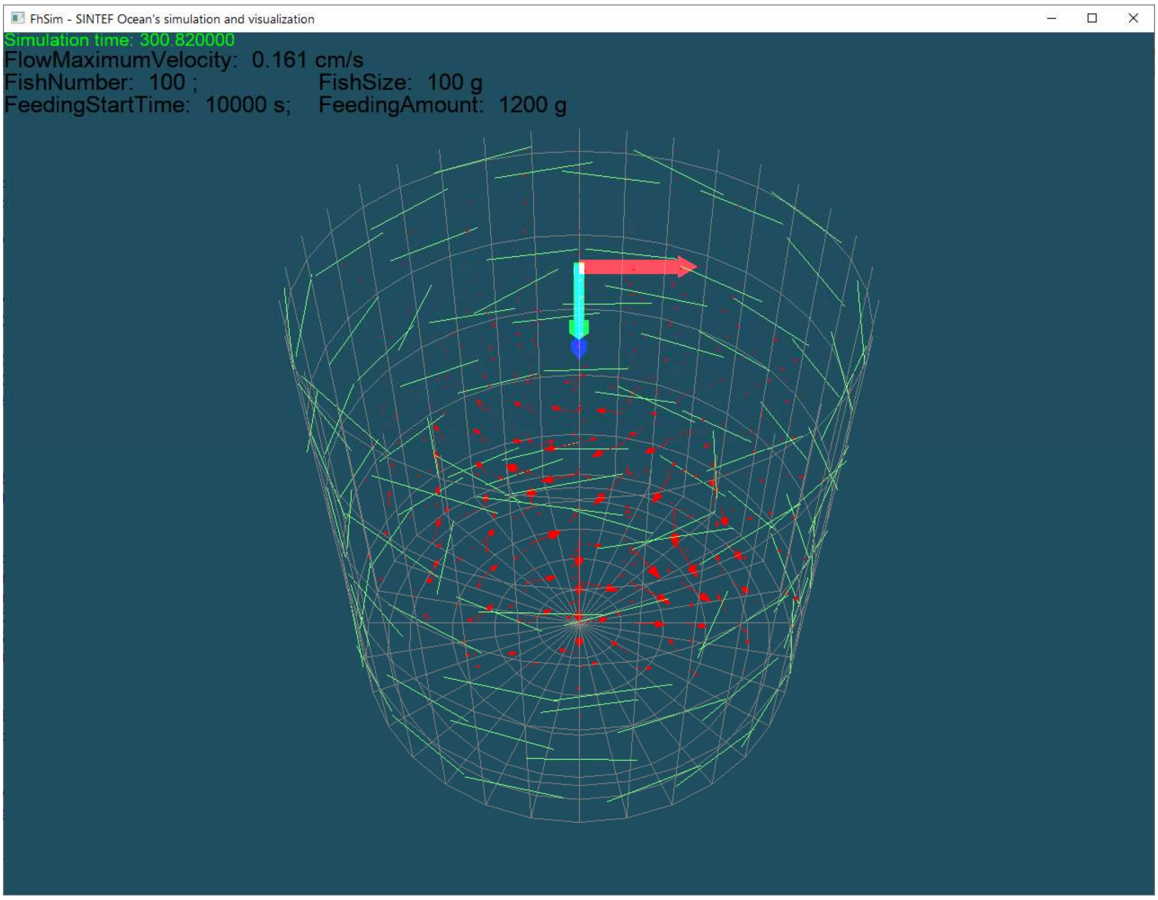


Figure 7: Screenshot of a simulation (FhSim) of 100 fish with a mean weight of 100 g in a 1 m diameter tank, and a qualitative illustration (red arrows of various sizes and directions) of the flow field generated from a NetCDF file.

A method for creating an artificial and simplified flow field for a tank was also developed. This method was mainly implemented to test the feed pellet distribution model for tank simulations (section 3.2.2) and is not tested and validated against real measurements or simulation results. The flow field that was artificially imposed presumed a circular tank with straight walls and a flat or close to flat bottom. It had a constant vertical velocity (outlet at the bottom) and a horizontal velocity component that had zero radial component and an angular component (polar coordinates) starting at zero at the origin and increasing linearly to a maximum value at the walls.

3.2.4. Coupling behaviour model with growth model

The growth model (task 4.1.4) needs fish swimming behaviour parameters such as average swimming speed and average feed ingestion in order to accurately estimate the growth. The swimming speed is dependent on the swimming behaviour, which in the model is dependent on the enclosure, closeness to other individuals, and parameters such as light and temperature (see Føre et al., (2009) for further details). In addition, the swimming behaviour is affected by whether the fish is feeding or not. How the fish reacts to feeding (swimming activity and resulting gut content as a result of the feeding) affects how much energy the fish has used through for instance swimming and digestion and obtained through feed consumption. Consequently, this may affect growth. Coupling of the growth model and behaviour model may then provide a way to simulate how the fish grow while taking into account the indirect effect that enclosure, stocking density, water speeds inside the tank as well as feeding regime has on the growth of the fish.

The original behaviour model had a simulation time step size of 1 s (Føre et al., 2009), while the newly implemented model has a step size of approximately 0.01 s due to e.g. the integration of a model for the net enclosure (Su et al., 2019). The growth model on the other hand has a step size of 1 h (3600 s). The coupling of these two simulation models through the FMI/FMU standard then proves challenging due to the difference in simulation time steps. The main aspect is that the slowest model, which in this instance is the fish behaviour model, will dictate the speed of the simulations. With the large discrepancy in timesteps the simulation would be impractical for our purposes in this project. Thus, an alternative was sought using surrogate modelling.

3.2.5. Surrogate model for fish behaviour

To be able to efficiently couple the fish behaviour model with the growth model the principle of surrogate modelling was considered to be a viable strategy. The surrogate model is a substitute or surrogate for the real behaviour model which is able to estimate results based on cage conditions and pass those to the growth model while also being able to communicate on the same time interval as the growth model. This enables co-simulation involving a model for the fish behaviour model and the fish growth model without directly using the original implementation of the fish behaviour model, and hence circumvent the challenges described in 3.2.4. The surrogate model does not directly consider the physics and biology of the fish and the enclosure, rather it is a function that gives output values as a function of given simulation input parameters. A surrogate model can be created through the use of statistical models or machine learning algorithms. Several types of surrogate models were tested, where the full list and further details can be found in Saad et al., (2023). A brief recollection of the method and testing presented in Saad et al., (2023) will now be given. The creation of a surrogate model requires training data that the model can train on in order to be able to estimate future outcomes or results. The quality and range of the training data is important for the performance of the resulting surrogate model, and different models may perform differently dependent on the process they are used to estimate the outcomes for. Further, it must be noted that the surrogate model only is tested for parameter variations within the stated parameter space. For a full scale commercial sea cage the parameter space that was used to train the surrogate models were: **1)** number of fish 2000 to 200 000; **2)** fish weight 0.1 to 10 kg; **3)** feeding true or false; **4)** feeding duration 1800 to 10 800 s; **5)** total feeding amount 0 to 5000 kg; **6)** initial gut content ratio 0 to 1 and **7)** wate current velocity 0 to 0.5 m/s. The outputs of the model is: **1)** feed ingestion; **2)** fish density (mean, max, standard deviation); **3)** swimming speed (mean, max, standard deviation) and **4)** relative swimming speed (mean, max, standard deviation). The Latin Hypercube sampling (Loh, 1996) scheme was adopted to produce input parameter samples that were evenly distributed over the input parameter space. The fish behaviour model (implemented in FhSim) was used to simulate and produce results (training data) for the generated input parameter samples (2000 different variations in total). A total of fourteen surrogate models were trained and tested on these data. The method, providing estimate prediction at model samples enable active learning (Cohn, 1996). The model is refined iteratively, meaning for instance that samples are created one at a time and that the current models predicted error estimate is prioritized. Summed up one can say that the samples of input parameters and resulting simulation results were used to train the surrogate models. Figure 8 (from Saad et al., 2023) describes which variable space were used in the training of the surrogate models and which output variables the surrogate models were optimized against. The figure also shows how a surrogate model may replace the actual behaviour model in simulations and the principle of how a surrogate model and FMU is created. Note that the behaviour model is not obsolete when a suited surrogate model is found. Rather, the surrogate model can be used instead of the actual behaviour model if the simulation inputs and net cage metrics is within the variable space the surrogate model was developed for. If the input parameters are outside the tested variation in input parameters the performance should be checked against the actual behaviour model and there may be a need for creating a new surrogate model that covers new use cases or an extended input variable space.

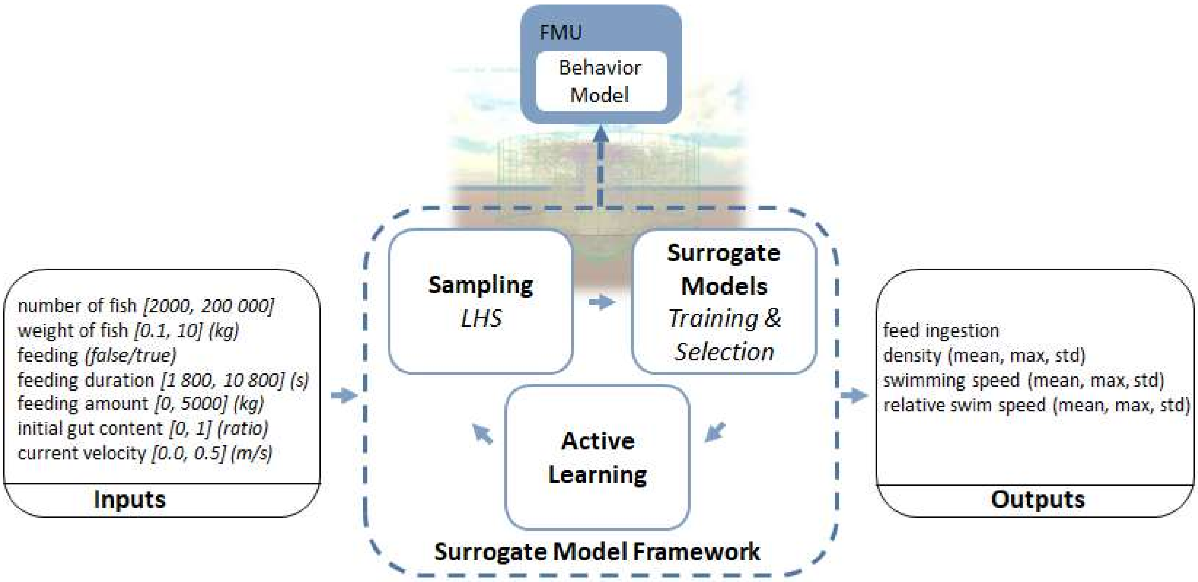


Figure 8: Schematics describing workflow of surrogate model development, input and output parameters of the surrogate model. Figure from Saad et al. (2023).

3.2.6. Modelling of other species – European Seabass

The salmon behaviour model functions by estimating a response due to environmental factors and parameters such as closeness to the enclosure walls or water temperature. The original model and iterations (Føre et al. 2009, 2013, 2016 and Su et al. 2019, 2023) focus on modelling of swimming behaviour of Atlantic salmon in sea cages under varying conditions. Kommedal (2024, In press) evaluates the behaviour of European seabass compared to Atlantic salmon and presents suggestions for modelling of different behavioural traits. Results from simulations incorporating the presented suggestions are also presented in Kommedal (2024, In press). The differences in behaviour between Atlantic salmon and European seabass were found through evaluation and comparison of the original behaviour model (Føre et al., 2009) and experiment results from 2022 from the Hellenic Centre for Marine Research (HCMR) according to Kommedal (2024, In press).

3.3. Technical implementation

3.3.1. Model summary

The model for swimming behaviour of Atlantic salmon is an individual based time domain model where by simulating several individual fish one also enables the simulation of the behaviour of a large population of fish in a sea based net cage or in land based tank. The user chooses if the model for a net cage or tank should be used, and then set input parameters such as number of fish and their size, feeding regime and gut content as well as water current velocity. The model simulates fish swimming and feeding behaviour during the simulation period, which is resolved in time. Model outputs are variables such as fish swimming speed, density distribution within the enclosure and feed ingestion.

3.3.2. Model implementation and auxiliary models

The behaviour model is implemented in SINTEF Ocean's in house software FhSim for time domain simulation of marine systems. FhSim is coded in the programming language C++. The fish behaviour model and other models and libraries in FhSim necessary to model fish behaviour in net cages or tanks is packaged into an FMU (Functional Mock-up Unit) to be accessible through the FMI (Functional Mock-up Interface) for usage in Kopl[2] without having to install FhSim. Accompanying models and libraries (within the SINTEF Ocean FhSim framework) that are not directly modelling the swimming behaviour of Atlantic salmon, but that are necessary in order to be able to simulate fish behaviour in net cages or tanks are:

- Environment model: Sets up the environment and stores information about water current and waves used in the simulation and is used by models to access water velocity and water particle accelerations. The coupling between the behaviour model and flow model (see section 3.2.3) is also performed through the environment model, enabling access to water velocities stored in the NetCDF file format (x-,y- and z-components) as a function of the position in the tank.

- Net cage model consisting of sub-models enabling the simulation of a deformable net cage, some of which are:

    - Net model: Structural model of the net. Also models deformation due to forces from current and waves as well as forces due to connected components (e.g. sinker tube). Also enables a dynamic boundary for the fish.

    - Sinker tube. Structural model modelling the deformation of the Sinker tube due to forces from current, waves, and connected components such as the net.

Of these accompanying models, the Environment model have had functionality added to it in order to be able to utilize results from the flow model and hence access flow velocity information stored in the NetCDF files. In addition, an option to use an artificial flow field for circular tanks was implemented.

3.3.3. Integration into the Virtual Laboratory and model usage

The behaviour model is packaged into an FMU (Functional Mock-up Unit) and made available through the Virtual Laboratory. The user can download the FMU for the behaviour model. It can be used as a standalone tool for both simulating fish behaviour in tanks and in fish cages (including the flow model results through NetCDF files). The user must download the appropriate FMU from the website (FMU for fish tank simulation or fish net cage simulation). In addition, the user must also download the tool for co-simulation (Kopl). A screenshot of the user interface in Kopl showing the input parameters for a cage fish simulation is shown in Figure 9. The correct FMU and path for the

[2] https://open-simulation-platform.github.io/kopl

FMU must be set, as well as desired input parameter values for the simulation, listed under the "Real variables" and "Parameters" tab. The parameters names, short descriptions, default values and units for a net cage fish simulation are listed in Table 1. The net cage dimensions which are set in the FMU are a diameter of 50 m and a total depth of 27 m whereas the vertical section is 15 m deep.

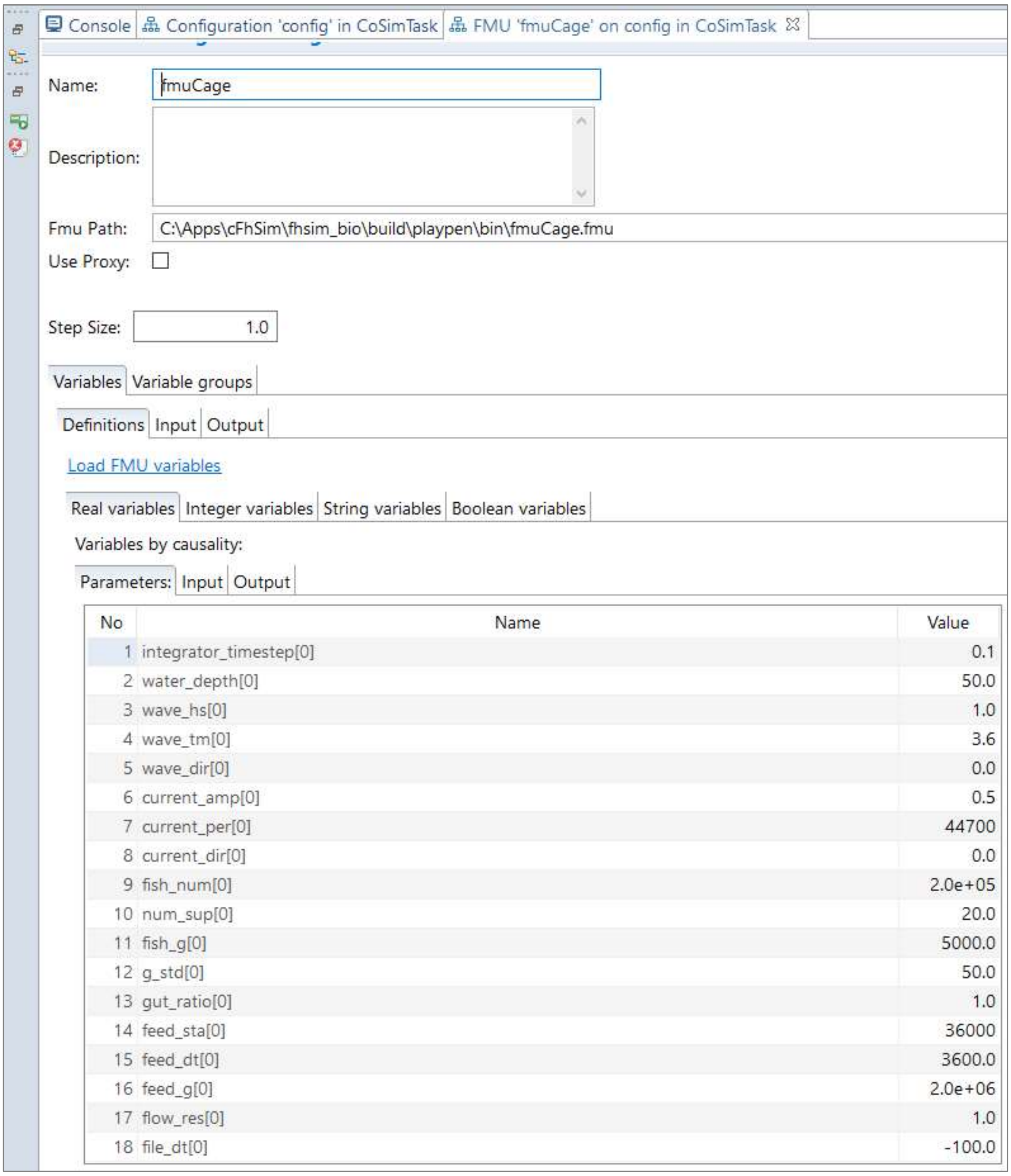


Figure 9: Screenshot of Kopl interface and Parameters tab for setting of simulation parameters (fish cage FMU). FMU name, path and parameters number, name and default values are shown.

Table 1: Cage FMU input parameters. Name, description, default values and units.

No	Name	Description	Default value	Unit
1	integrator_timestep[0]	Time step for integrator	0.1	s
2	water_depth[0]	Water depth	50	m
3	wave_hs[0]	Significant wave height	1	m
4	wave_tm[0]	Wave mean period	3.6	s

5	wave_dir[0]	Wave direction	0	radians
6	current_amp[0]	Amplitude of tidal current	0.5	m/s
7	current_per[0]	Period of tidal current	44700	s
8	current_dir[0]	Direction of tidal current	0	rad
9	fish_num[0]	Number of fish in total	2e5	-
10	num_sup[0]	Number of fish per super individual	20	-
11	fish_g[0]	Mean fish weight	5000	g
12	g_std[0]	Standard deviation of fish weight	50	g
13	gut_ratio[0]	Gut content ratio	1	
14	feed_sta[0]	Feeding start time	36000	s
15	feed_dt[0]	Feeding duration	3600	s
16	feed_g[0]	Total amount of feed	2e6	g
17	flow_res[0]	Flow response parameter of fish	1.0	-
18	file_dt[0]	Period to save states of each fish	-100 (not set)	s

In addition to the input parameters chosen by the user, one can set some parameters equal to values sent by a connected FMU. These input parameters are, see Figure 10, significant wave height, mean wave period, wave direction, current velocity in two depth layers (surface and bottom) as well as current direction in the corresponding depth layers.

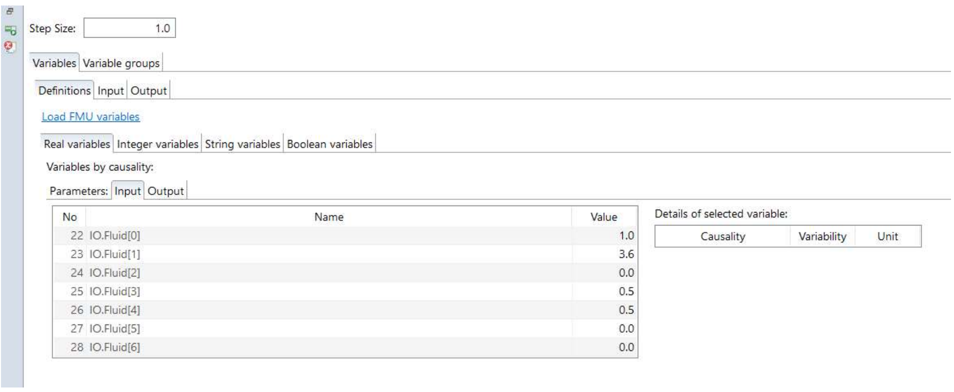


Figure 10: Screenshot of Kopl interface for inputs from connected FMU (fish Cage FMU).

The fish cage FMU also produces output values, some of which can be reported to a connected FMU (see Figure 11, marked as IO.Fish). Other parameters, that are not used by connected FMUs, include information on the environment (fmiOutput.IO_Fluid), fish cage bottom position (fmiOutput.Fish_BotOutPos[1-3] and cage volume (fmiOutput.Fish_CageVolume). Other output variable values of interest from the behaviour model are e.g. fish density (mean, maximum and standard deviation), fish swimming speed (mean, maximum and standard deviation) and the amount of feed the fish has ingested (see Figure 12 for extended output variable list). Further, the co-simulation tool (Kopl) available through the Virtual Laboratory provides the possibility of showing graphs of chosen output variables.

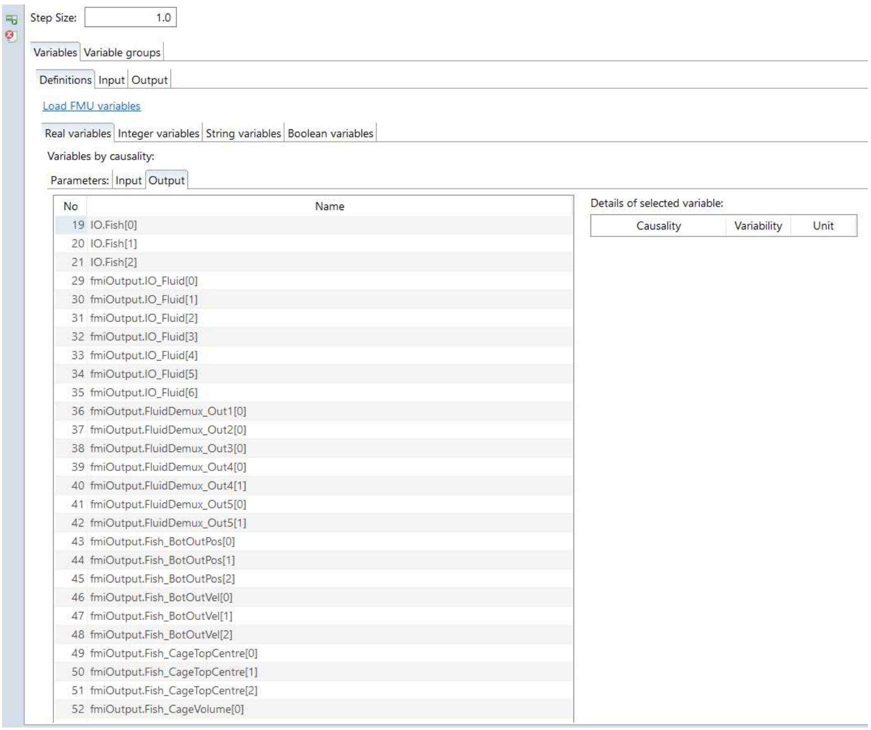


Figure 11: Screenshot of Kopl interface for outputs from fish Cage FMU.

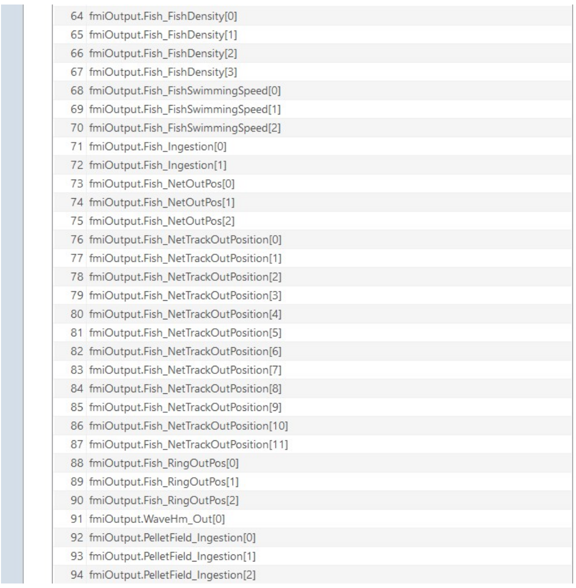


Figure 12:: Screenshot of Kopl interface for outputs from fish Cage FMU. Variable values include fish density, fish swimming speed and fish feed pellet ingestion.

4. Results and Discussion

4.1. Behaviour modelling in tanks – wall avoidance

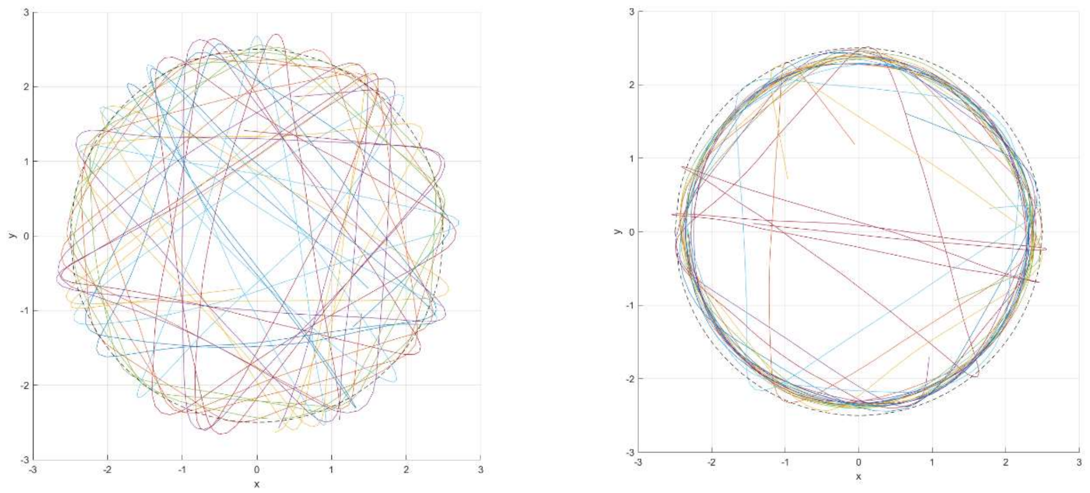


Figure 13: Simulated (FhSim) swimming trace (path) plotted in Matlab for selected fish in a simulation of a fish population in a circular tank with 5 m diameter when using the modified algorithm to detect nearest wall boundary. Left: When preferred distance to tank walls is set too low. Right: Increased preferred distance to walls. A similar effect may be seen by also reducing the update time step of the simulation.

Although the implemented brute force method identified the correct closest wall boundary element for each fish, the fish model still was not able to keep the fish entirely inside the enclosure (Figure 13, left). This is believed to be an issue partly related to time step size and the set preferred minimum distance to wall boundaries in the simulations. The fish model also has a limit for how quickly it may change direction. This means there will be a delay from when the fish model e.g. discovers that it is too close to the tank wall to it having changed the swimming direction. This rate was set to avoid unphysical representation of directional change (Føre et al., 2009). The chosen preferred minimum distance to walls and the simulation update time step may also affect the simulated fish behaviour towards cage boundaries. Too large time steps in relation to the preferred minimum distance to the walls may result in the modelled fish discovering that it is too close to the walls too late to have time to avoid the wall with the set rate of directional change, given the swimming speed of the fish. The fish model may also cross the cage boundary before the wall is “discovered”. Increasing the preferred distance improved the response (see example in Figure 13, right). Reducing the update time step for the simulation may also improve the results in terms of reducing how much the fish cross the boundary. It is likely that the fish model “discovers” that it is too close to the wall earlier when the update time step size is reduced. The effect of reducing the simulation update time step obviously has some limits which is dependent on the original step size and the simulated fish swimming speed as well as the set minimum distance to the boundary. Testing indicated that adjustment of the simulation time step in combination with adjustment of the fish’s preferred distance to the walls may be used to tune the model response such that the modelled fish mostly stay inside the modelled enclosure and do not excessively cross the enclosure boundaries.

4.2. Feed pellet distribution modelling in tanks

Since the tank simulation model artificially simulates fish behaviour and feed distribution it is possible to induce unphysical conditions on the model such as water flow across the tank boundaries. This will lead to feed passing through the tank walls. However, one should not induce these conditions in tank simulations. Realistic flow fields for tanks, either artificially created by formulas or imported with the NetCDF file format from other sources (see section 3.2.3) will partly prevent the feed from laterally spreading outside the tank volume. Ideally, no velocities normal (perpendicular) to the walls should exist, but due to the grid (discretization) in the numerical model net transport of water and consequently feed pellets may occur numerically across the tank boundaries. Also, modelled diffusion may cause the feed pellets to cross the cage boundaries. In the implementation of the distribution model the grid cells are prisms with square corners (cartesian grid cells). Each surface uses a velocity to calculate the flux. For uniform flow fields this usually means that mass conservation is not violated, but for a non-uniform flow field like the flow field in a tank this grid may induce non-physical results where mass is not conserved in the calculations. Reducing grid cell size and modifying velocity formulation on grid cell surfaces may mitigate some of these challenges, but these techniques were not further investigated. In this particular example for the flow field, with velocity and transport of feed pellets possibly having a small radial component and larger angular component (polar coordinates), the use of a cartesian grid (square grid cells) may induce imbalance in the calculated transport in and out of the cells. Føre et al. (2018) avoided feed pellet transport across the tank walls by modification of the pellet model as well as prohibiting flow across the tank walls. This method was not implemented in the present model and was not further evaluated.

4.3. Surrogate model for fish behaviour in net cages

Of the fourteen different surrogate models that were tested for simulation of fish populations in sea based net cages, among them Support Vector Regression (SVR), Artificial Neural Network (ANN) and Random Forest (RF), Gaussian Process Regression (GPR) gave the overall best results while Inverse Distance Weighting (IDW) gave the worst results. The surrogate models were evaluated based on R^2 score, Mean Square Error, Mean Absolute Error and Normalized Root Mean Squared Error, where the GPR model had the highest R^2 value while also having the lowest values for the other metrics describing the performance of the surrogate model (Saad et al., 2023). Figure 14 and Figure 15 show comparison between surrogate model results and ground truth (behaviour model results) for three different surrogate models over two different output variables. The two variables are mean swimming speed and mean fish density. From the figures one can see how well the GPR (Gaussian Process Regression) and KPLS (Kernel Partial Least Squares) estimates the output variables compared to the IDW (Inverse Distance Weighting) method. In these two figures, the blue lines represent the target output value, while the red dots represent the estimated output value. Table 2 (Saad et al., 2023) presents the average values of the different performance metrics for the three different models presented in Figure 14**Error! Reference source not found.** and Figure 15**Error! Reference source not found.**. Generally, good performance of the models is indicated by high (close to one) R^2 value and low MSE, RMSE, MAE and NRMSE values.

Although the creation of a surrogate model is demanding, labour intensive and specific to the purpose for which it has been created (2000 simulations across the input parameter space were performed), it is beneficial for many cases. In this instance a surrogate model facilitates for co-simulation between the fish behaviour model and the growth model. In addition, a result from the GPR surrogate model - simulating up to 3 hours of feeding in the presented iteration - may use less than a millisecond to produce an estimate. The actual behaviour model, albeit able to simulate a fish population faster than real time on a powerful computer, will use significantly longer time than a typical surrogate model. This enables quick estimates for average or extreme values where the use of a method modelling the physics of the system would use significantly longer time.

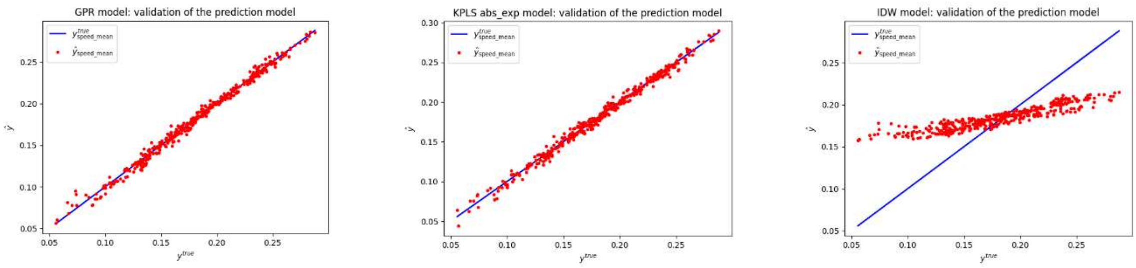


Figure 14: The ground truth (y^{true}) from the simulations (blue) in FhSim versus the model predictions (red) of mean swimming speed ($\hat{y}$). From the left: GPR, KPLS and IDW model. Figures from Saad et al. (2023).

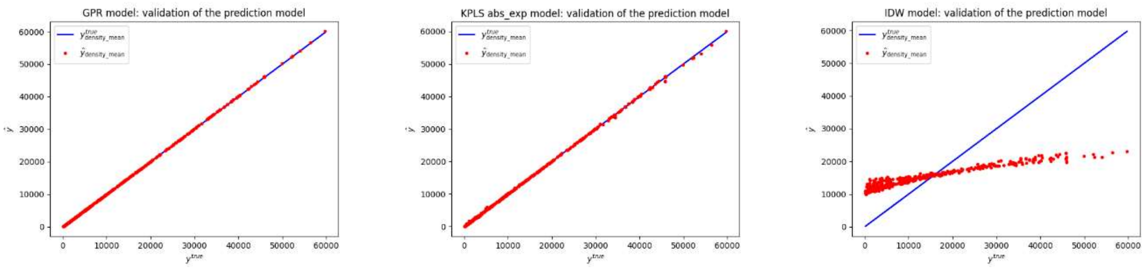


Figure 15: The ground truth (y^{true}) from the simulations (blue) in FhSim versus the model predictions (red) of mean fish density ($\hat{y}$). From the left: GPR, KPLS and IDW model. Figures from Saad et al. (2023).

Table 2: Three different surrogate models and their average performance metrics. High R^2value and low MSE, RMSE, MAE and NRMS values indicate closeness to target output values. The table is an excerpt from table in Saad et al. (2023).

Model	R^2 score	MSE	RMSE	MAE	NRMSE
KPLS	0.989	0.0004	0.019	0.011	0.042
IDW	0.412	0.0230	0.152	0.119	0.324
GPR	0.992	0.0003	0.017	0.010	0.037

4.4. Surrogate model for fish behaviour in tanks

Similar to how a surrogate model and corresponding FMU for the fish behaviour in open net cages was developed and created (section 3.2.5), a surrogate model and corresponding FMU for the fish behaviour in tanks will be created as part of deliverable D4.8. The method will follow the same procedural steps as was done to create the surrogate model for fish behaviour in open net cages. Differences will be the input parameter space, as the ranges of input parameter values (e.g. number of fish, size of fish, amount of feed, water velocity) will be different for a tank than for a full-size open sea based net cage. The results, e.g. fish swimming speed, fish density and average feed ingestion, may also be different than for open net cages. Other differences may be the performance results for the different surrogate models. The best performing surrogate model when testing on tank specific simulation data will be used to model the fish behaviour in tanks.

4.5. Fish behaviour – European seabass

Kommedal (2024, In press) states that comparison between the original behaviour model (Føre et al., 2009) and the results from the experiments with European seabass at HCMR in 2022 indicate vertical swimming behaviour different from what is observed for Atlantic Salmon. The European seabass in the experiments tends to swim towards the surface in the morning and evening, and had increased swimming activity (speed) during morning and evening, while staying deeper or at least more evenly distributed the rest of the day. Limitations regarding vertical camera position (used for observation during the experiments) and possible effect on counts of fish were noted. In addition, it was indicated that both optimal and maximum swimming speed and probably also preferred swimming speed increased with increasing water temperature. In the model presented by Kommedal (2024, In press) the main differences from the model presented in Føre et al., (2009, 2013, 2016) was that temperature preferences, light preferences and feeding behaviour were removed from the model for seabass. A depth preference was added, as the model for Atlantic salmon did not include this directly. This does not necessarily mean that European seabass does not have temperature or light preferences. It may mean that available data does not give enough information regarding these preferences. The vertical swimming depth for E. seabass seems to be governed by the time of day. The vertical swimming behaviour of A. salmon seems to be affected by light intensity levels (see e.g. Føre et al., 2009, 2013). The salmon seem to seek towards the surface if the light level is too low and move deeper if the surface light level is too high. Føre et al. (2013) presented comparison between simulations and experiments with farmed A. salmon and submerged lights in sea cages with a thermally stratified environment (experiments presented by Oppedal et al., 2007), where it was indicated in the simulations that the way behaviour response to light and temperature were modelled were often able to reproduce the swimming depth (or vertical fish distribution) seen in the experiments. In Føre et al. (2013) it was noted that the combined response due to light and temperature and how the model simulates the trade-off or weighting between the importance of the two parameters (as they both may not be within preferred ranges) may be important. Although it seems that the swimming depth of E. Seabass is dependent on the time of day (Kommedal, 2024 In press), it may be that other parameters contribute to this behaviour. Compared to A. salmon, E. seabass had, based on the experiment results from HCMR in 2022, (discussed in Kommedal (2024, In press)), a slightly different response to temperature, where the optimal and maximum swimming speed seemed to increase with increasing temperature, which does not impact the vertical swimming behaviour directly. It was noted in Kommedal (2024, In press) that the Mediterranean where the experiments were conducted have water with smaller temperature changes in the water column as well as clearer water, meaning less reduction in light levels with depth, compared to e.g. typical Norwegian coastal conditions where farming of A. salmon is common, which may mean that obtaining data on such preference may be challenging regarding E. Seabass. The present behaviour model for A. salmon calculates a swimming response based on driving factors such as preferred light level and water temperature. More knowledge on the preferences of E. Seabass regarding these and other driving factors is thought to be important to improve modelling of E. Seabass swimming behaviour. Training-based surrogate models may be used for parameter identifications and reproduction of the observed fish swimming patterns. Research on this subject is a matter for further studies and development.

4.6. New knowledge and added functionality in the behaviour model

Developments for fish behaviour modelling has been achieved and new functionality has been added to the behaviour model. The development in modelling and updates to the model, described in detail in section **Error! Reference source not found.**, are:

- Adaptation of the model to be able to simulate individual fish and a fish population in a circular tank
- Adaptation of the feed pellet distribution model for use in circular tanks
- Coupling of the fish behaviour model and fluid flow model to enable access to and usage of the fluid velocity fields found for tanks in task 4.1.3.
- Establishing a procedure for creating a surrogate model for fish behaviour in both open net cages and tanks.
- Creating a surrogate model and a FMU for modelling of the swimming and feeding behaviour of Atlantic salmon in net cages which
    - Enables fast simulation of population response
    - Facilitates the integration between the behaviour model and the growth model
    - Enables creation of a surrogate model (and FMU) for fish behaviour in circular tanks. *(The creation of a surrogate model for tanks is in progress as this report is written.)*
- Creation of original FMUs for both fish cage and fish tank behaviour simulation. These FMUs have been made available through the Virtual Laboratory.
- Discussion and evaluation of existing knowledge and knowledge needs regarding the use of the existing fish behaviour model formulation for simulation of other species such as European Sea bass.

4.6.1. Behaviour model capabilities

The behaviour model is able to model the fish behaviour on an individual level, where the fish swimming behaviour due to external factors such as the enclosure boundaries, temperature and the presence of feed is estimated. This means that one is able to obtain simulated behaviour for each fish in the population, gaining information about for instance position in the cage and feed ingestion. On an aggregated level or population scale one can get estimates of for instance fish densities as well as swimming speed and average feed ingestion. These variables can be important to know for assessment of the effect of enclosure or environmental parameters as well as for evaluating performance such as fish growth. The behaviour model can simulate individual fish swimming behaviour and consequently estimate fish population variables in both open net cages and in tanks.

4.7. Net cage FMU simulation results

Kopl provides a user interface for usage of FMUs for simulation. Through the interface one gets an overview of input parameters and the option to edit these. The tool also provides real-time visualisation and post-processing of simulation results, where variable values can be plotted in the user interface. Figure 16 to Figure 19 show examples of the visualisation and plotting of simulation results using Kopl.

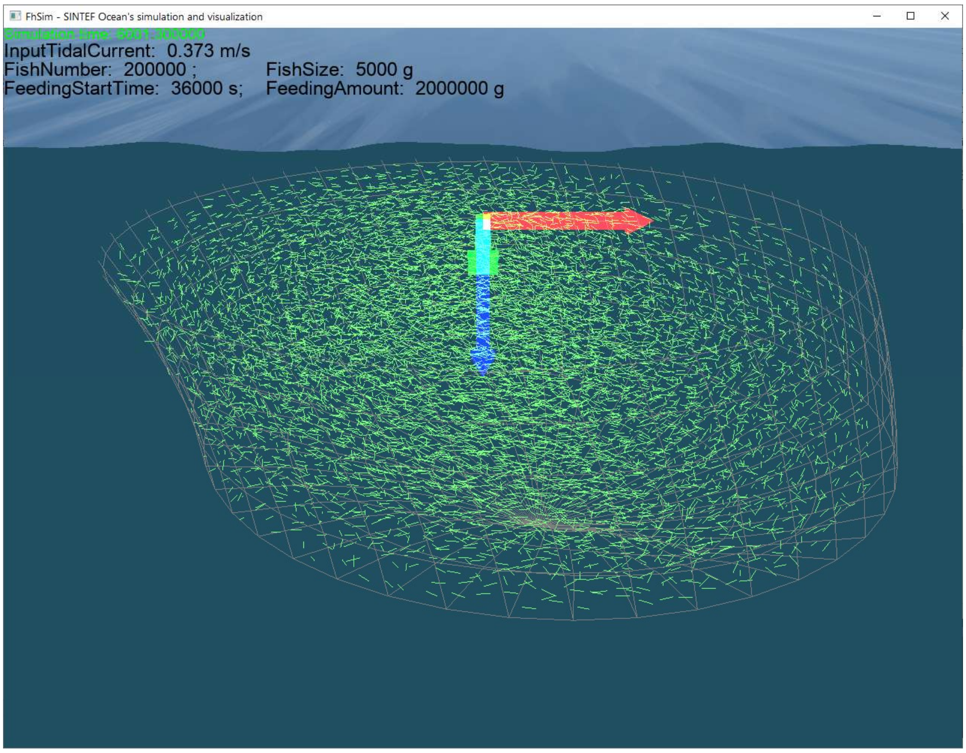


Figure 16: Screenshot of the real-time visualisation of fish and enclosure in Kopl using FMUs exported from FhSim. This figure shows an example when periodic tidal current and irregular waves are considered for the simulation of cage deformations and fish swimming behaviour.

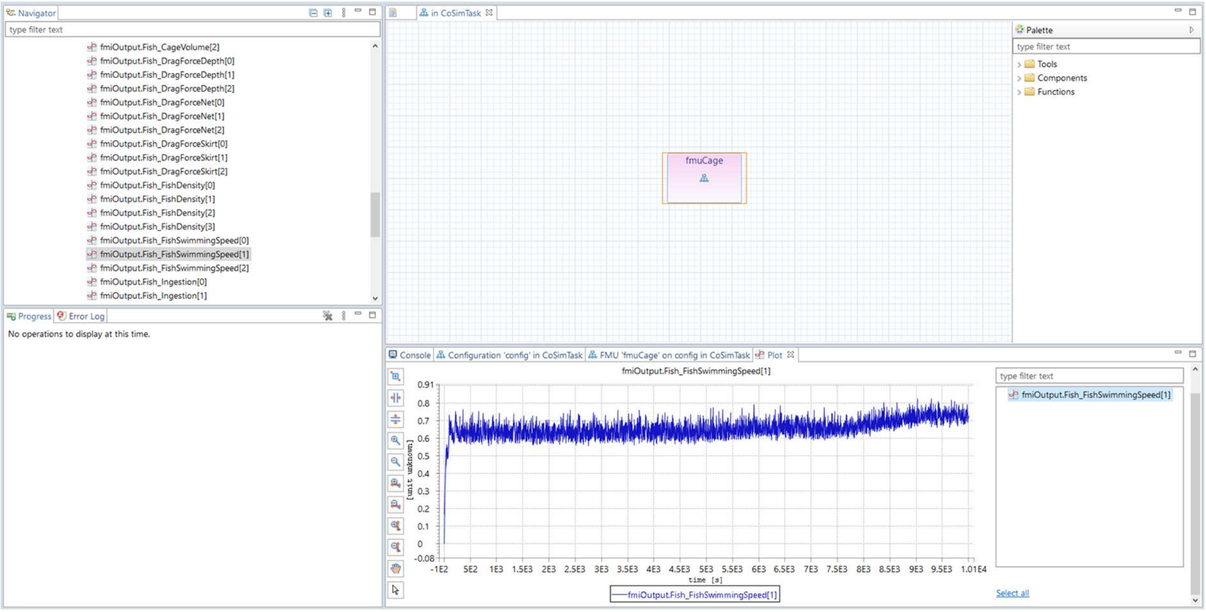


Figure 17: Screenshot of user interface of co-simulation tool Kopl. The figure shows the chosen FMU, selection of output variable (fish swimming speed) and plotting of the values of the chose variable as a function of time.

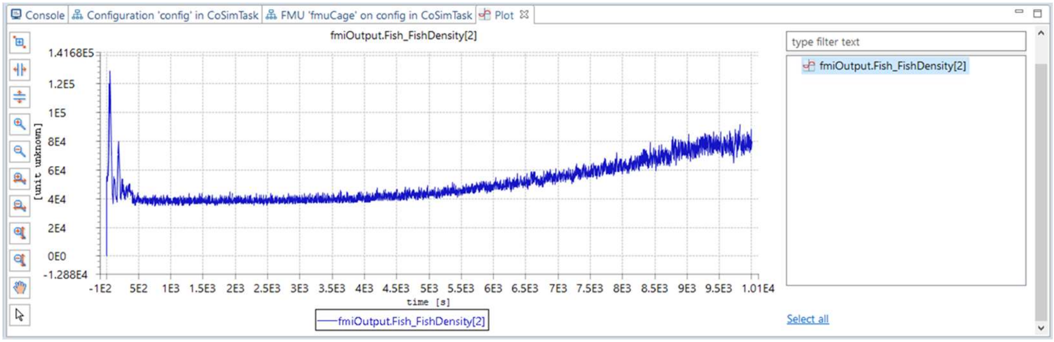


Figure 18: Screenshot of user interface of co-simulation tool Kopl. The figure shows an example of simulation results (fish density) plotted as a function of time.

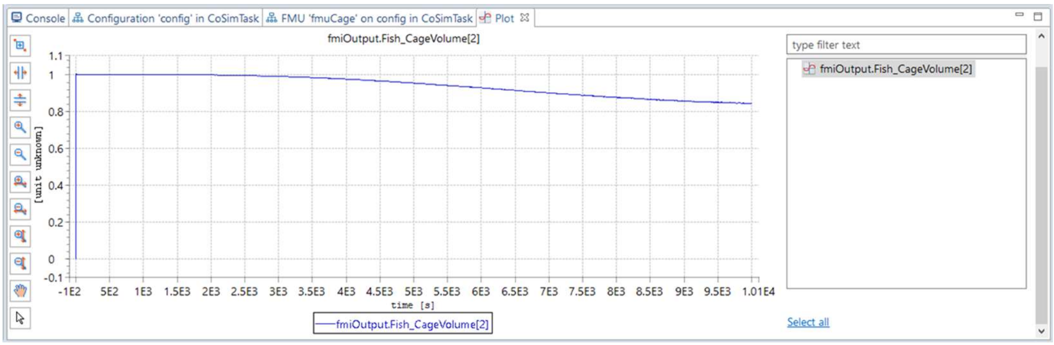


Figure 19: Screenshot of user interface of co-simulation tool Kopl. The figure shows an example of simulation results (cage volume) plotted as a function of time.

5. Conclusion

The fish behaviour model is now able to simulate fish populations in tanks. The fish reacts to the flow, feed pellets and tank boundaries.

The super-individual model enables simulations of large fish populations. Dependent on computer performance, simulations can run in real time or faster.

The surrogate model for fish behaviour gives reliable results. It is very fast and serves as a viable solution to mitigate the challenges with large differences in time steps that arise in co-simulation with the growth mode.

It is found that more data are probably needed to parameterise the behavioural responses (e.g., towards light and temperature) of European Seabass in the present model formulation.

6. Appendix

No appendix present.

7. References

Alver, M., Alfredsen, J.A., Sigholt, T., 2004. Dynamic modelling of pellet distribution in Atlantic salmon (Salmo salar L.) cages. Aquacultural Engineering. 31. 51-72. 10.1016/j.aquaeng.2004.01.002.

Alver, M.O., Skøien, K.R., Føre M., Aas, T. S., Oehme, M., Alfredsen, J.A., 2016. Modelling of surface and 3D pellet distribution in Atlantic salmon (Salmo salar L.) cages, Aquacultural Engineering, Volumes 72–73, 2016, Pages 20-29, ISSN 0144-8609, https://doi.org/10.1016/j.aquaeng.2016.03.003.

Cohn, D.A., Ghahramani, Z., Jordan, M.I., 1996. Active learning with statistical models. Journal of artificial intelligence research, 4:129–145, 1996.

Espmark, Å.M., Kolarevic, J., Åsgård, T., Terjesen, B.F, 2017. Tank size and fish management history matters in experimental design. Aquaculture Research, 48, 2876-2894.

Føre, M., Dempster, T., Alfredsen, J. A., Johansen, V., Johansson, D., 2009. Modelling of Atlantic salmon (Salmo salar L.) behaviour in sea-cages: A Lagrangian approach, Aquaculture, Volume 288, Issues 3–4, Pages 196-204.

Føre, M., Dempster, T., Alfredsen, J.A., Oppedal, F., 2013. Modelling of Atlantic salmon (Salmo salar L.) behaviour in sea-cages: Using artificial light to control swimming depth, Aquaculture, Volumes 388–391, 2013, Pages 137-146, ISSN 0044-8486, https://doi.org/10.1016/j.aquaculture.2013.01.027.

Føre, M., Alver, M., Alfredsen, J.A., Marafioti, G., Senneset, G., Birkevold, J., Willumsen, F.V., Lange, G., Espmark, Å., Terjesen, B.F., 2016. Modelling growth performance and feeding behaviour of Atlantic salmon (Salmo salar L.) in commercial-size aquaculture net pens: Model details and validation through full-scale experiments, Aquaculture, Volume 464, 2016, Pages 268-278, ISSN 0044-8486, https://doi.org/10.1016/j.aquaculture.2016.06.045.

Føre, M., Alver, M.O., Alfredsen, J.A., Senneset, G., Espmark, Å., Terjesen, B.F., 2018. Modelling how the physical scale of experimental tanks affects salmon growth performance, Aquaculture, Volume 495, 2018, Pages 731-737, ISSN 0044-8486, https://doi.org/10.1016/j.aquaculture.2018.06.057.

Johannesen, Á., Patursson, Ø., Kristmundsson, J., Dam, S.P., Mulelid, M., Klebert, P., 2022. Waves and currents decrease the available space in a salmon cage. Plos One 17, e0263850.

Johansson, D., Laursen, F., Fernö, A., Fosseidengen, J.E., Klebert, P., Stien, L.H., Vågseth, T., Oppedal, F., 2014. The interaction between water currents and salmon swimming behaviour in sea cages. PloS One 9, e97635.

Klebert, P., Su, B., Nissen, O., Kvæstad, B., 2023. Response of Atlantic salmon in flexible sea cages to waves and currents: Measurements at farm-level and modeling. Appl. Ocean Res. 138, 103599. https://doi.org/10.1016/j.apor.2023.103599.

Kommedal, M., 2024 (In press). Individual Modelling of European Seabass Behaviour. Norwegian University of Science and Technology, Faculty of Information Technology and Electrical Engineering, Department of Engineering Cybernetics, Trondheim, Norway, 2024. Master thesis.

Loh, W.-L., 1996. On latin hypercube sampling. The annals of statistics, 24(5):2058–2080, 1996.

Oppedal, F., Juell, J.E., Johansson, D., 2007. Thermo- and photoregulatory swimming behaviour of caged Atlantic salmon: implications for photoperiod management and fish welfare. Aquaculture 265, 70–81.

Reite, K., Føre, M., Aarsæther, K.G., Jensen, J., Rundtop, P., Kyllingstad, L.T., Endresen, P.C., Kristiansen, D., Johansen, V., & Fredheim, A., 2014. FHSIM — Time Domain Simulation of Marine Systems. Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. Volume 8A: Ocean Engineering. San Francisco, California, USA. June 8–13, 2014.

Saad, A., Su, B., Bjørnson, F.O., 2023. A Web-Based Platform for Efficient and Robust Simulation of Aquaculture Systems using Integrated Intelligent Agents. Procedia Computer Science, Volume 225, 2023, Pages 4560-4569, ISSN 1877-0509, https://doi.org/10.1016/j.procs.2023.10.454.

Scheffer, M., Baveco, J.M., DeAngelis, D.L., Rose, K.A., van Nes, E.H., 1995. Super-individuals a simple solution for modelling large populations on an individual basis. Ecol. Model. 80, 161–170. https://doi.org/10.1016/0304-3800(94)00055-M.

Su, B., Reite, K., Føre, M., Aarsæther, K. G., Alver, M. O., Endresen, P. C., Kristiansen, D., Haugen, J., Caharija, W., Tsarau, A., 2019. A Multipurpose Framework for Modelling and Simulation of Marine Aquaculture Systems. Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering. Volume 6: Ocean Space Utilization. Glasgow, Scotland, UK. June 9–14, 2019.

Su, B., Bjørnson, F.O., Tsarau, A., Endresen, P.C., Ohrem, S.J., Føre, M., Fagertun J.T., Klebert, P., Kelasidi, E., Bjelland, H.V., 2023. Towards a holistic digital twin solution for real-time monitoring of aquaculture net cage systems, Marine Structures, Volume 91, 2023, 103469, ISSN 0951-8339, https://doi.org/10.1016/j.marstruc.2023.103469.

Document Information

EU Project	No 871108	Acronym	AQUAEXCEL3.0
Full Title	AQUAculture infrastructures for EXCELlence in European fish research 3.0		
Project website	www.aquaexcel.eu		

Deliverable	N°	D4.4	Title	Final model for fish behaviour
Work Package	N°	WP4	Title	JRA1 - Technological tools for improved experimental procedures
Work Package Leader	Finn Olav Bjørnson			
Work Participants	SINTEF Ocean			

Lead Beneficiary	SINTEF Ocean, 11
Authors	Per Christian Endresen, SINTEF Ocean, Per.Christian.Endresen@sintef.no Biao Su, SINTEF Ocean, Biao.Su@sintef.no
Reviewers	Finn Olav Bjørnson, SINTEF Ocean, finn.o.bjornson@sintef.no Marie-Laure Bégout, IFREMER, Marie.Laure.Begout@ifremer.fr

Due date of deliverable	30.09.2024
Submission date	30.09.2024
Dissemination level	PU
Type of deliverable	R-Other

Version log			
Issue Date	Revision N°	Author	Change
04.09.2024	0.8	Per Christian Endresen, Biao Su	First version for internal review
18.09.2024	1.0	Per Christian Endresen, Biao Su	Second version after internal review