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Context analysis of Offshore Fish Farming

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Context analysis of Offshore Fish Farming

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Abstract. The in-land and nearshore fish farming is facing capacity limitation and onshore push-out regulations. Huge technological innovations are rapidly evolving toward developing competitive Offshore fish farming. These technological innovations are mainly targeting to innovate new farming concepts that dynamically stable, reliable and compatible with offshore environmental loads and conditions. The dynamic operational behaviour of each farming concept is quite complicated. It is a combination of reinforcing behaviours (Loads, cage deformations, welfare issues, e.g. escaping, stress-related disease) and leveraging behaviours (Biofouling-cleaning, Deterioration-maintenance) and all influenced by fluctuating and harsh environmental loads and conditions. Therefore, the purpose of this paper is to analyse the context of offshore fish farming and explore quantitative descriptions of its reinforcement and leveraging behaviours. The context analysis is a well-known method within systems engineering methodology to illustrate and extract critical interfaces. The context analysis is considered as the first step in building simulation model to quantify the impact of systems interfaces on the entire farming economics, i.e. income and cost.

1. Introduction

The profitability of aquaculture production is highly dependent on the accumulated healthy bio-bass at the end of the production season, and on the other side, operating cost (Crew, feeding, energy, net-related services), maintenance cost (failures, inspections), and the associated economic and environmental impacts [1]. At the moment, the near-shore, coastal and fjords-located fish farms are more profitable than land-based farms due to investment, water treatment, etc [2]. However, the chances to install more fish farms at near-shores are getting lower over time due to the capacity limitations and high social and environmental issues. Therefore, the trend is to move offshore (at sea, open sea and ocean) which is a new era for the cultured fish industry. From a technical and economic perspective, offshore farms shall withstand the harsh environmental loading at exposed sites, which requires high investment cost. However, the scale of offshore fish farms might ensure the profitability of such investment.

Innovative concepts for offshore fish farming are rapidly increasing [3], [4]. The platform-like farm concept (Ocean farm 1, SalMar) is in operation. The Vessel-like farm concept (Havfarm) is planned to be installed in 2019 and has functions to provide optimal water exchange and farm mobility. The Submarine-like farm concept (Preline) is planned to be constructed in the future and aims to avoid high loads at sea surface. Closed deep-water sphere farm concept (Aquapods) is also planned to be constructed and aims to avoid the spread of pollutants and reduce the installation impacts of the surroundings, collect organic faeces and prevent escapes [5]. The profitability model (revenue and cost) of offshore fish farming is it is needed to evaluate such



concepts. However, it is complex and relying heavily on the environmental variables and farming concept (on-surface, submersed). It is needed, not only for feasibility and cost-volume analysis studies, but for design concept review and modification (functions, design parameters) and mapping the impact of new technologies [4], [6], at the design phase. It also helps to determine the optimal operating policy at utilisation phase. The design concepts shall ultimately aim to increase the production rate (at least reduce losses) and cut-down the operating cost (energy, cleaning and maintenance), besides ensuring the environmental compatibility to withstand the harsh loading and operating conditions. The complexity of developing profitable model that represent the offshore fish farming concepts and operations is related to the dynamic relationships among five main processes [7]: fish welfare [8] and growth process (eating, swimming [9], growing [10], [11], [12], infection [13], [14], [15], sea-lice growth [16], [17], escaping [18]), the production process (supply, storage, feeding [19], control the artificial conditions, energy consumption [20]), farm assets (stability, deterioration [21], bio-fouling [22]), farm services (net cleaning, infection treatment, maintenance), and the farm site and its environmental loads and conditions [23](waves, current velocities, water temperature, salinity rate, diseases, access-ability).

The impact of all previously mentioned dynamic processes shall be considered to develop a profitability model of offshore fish farming. There are several models developed to estimate the impact of one or more of these dynamic processes. Anyadike et al.,[24] have reviewed the aquaculture production models. It was highlighted that there is a lack of utilising the systems dynamic simulation to estimate the impact of fish farms within their environmental context and especially sea-based ones [25]. Hamze et la.,[17] used system dynamics simulation, and Alaliyat and Yndestad [15] agent-based simulation to predict the impact of diseases within fish farms. Deterioration of assets is vital to predict the potential failures, unintended maintenance visits and associated costs. Deterioration estimation depends on physical modelling and simulation where the applied stresses due to environmental loading are accumulated and used for failure predictions, as done in [26] and [27]. In this regard, there are several structural assessment studies that can be used for deterioration modelling, for example, Mooring system [28], Cage system [29] Feeding pipes [30]. Moreover, there are recent studies for structural assessment for offshore fish farm concepts for example Havfarm concept [31], [32] and Ocean farm 1 [33].

It is quite clear that each previously mentioned dynamic processes is related to a specific domain of science and engineering and requires specific modelling and simulation method. Fish growth and welfare is a biological process and requires specific biological modelling and simulation tools. Production process is more related to be an industrial engineering and management issue. Fish asset is related to mechanical and structural engineering where several engineering modelling and simulation tools are used FEM, CFD, Systems dynamic. Farm services is a combination of maintenance management, treatment management and bio-fouling management. Therefore, multi-method modelling and system dynamic modelling have been used to integrate the estimations of the impact for one or more of these dynamic processes. For example, system dynamics modelling is used in aquaculture (Shrimp [34], [35], Tuna ranching [36]) and fishery [37] industries to estimate the the impact of environmental changes, consumer behaviours and over-fishing management. For marine cage aquaculture, Chateau and Chang [25] developed a system dynamics model to estimate the profitability. Even though this model ignores cost factors which are required to estimate profitability as a surplus remaining after total costs are deducted from total revenue, it illustrates the impact of availability of dissolved oxygen in the water, feed floatability, delays between production seasons on overall profitability.

Offshore fish farm concepts and operations affect and affected by all these dynamic processes. An integrated model is required to enable the estimation of the cost and revenue over the lifetime of the offshore fish farm. Therefore, the objective of this paper is to conceptualise profitability model that are affected by site conditions, environmental loading, production process, fish growth and welfare process, asset deterioration process and farm services. The model conceptualisation

is the first step to develop a robust simulation model in the future using a multi-method simulation package, e.g. Anylogic, Numerus. The simulation architecting process is used to conceptualise the simulation model that considers context and interfaces.

2. Purpose analysis

As mentioned in the introduction section, the objective is to conceptualise a profitability simulation model for offshore fish farming. The purpose of this model is to predict the potential income and costs over the entire farm lifetime "utilisation period". The income is mainly related to the total biomass (in kg) that are accepted to enter the production seafood process, which means the dead and unhealthy fishes will be deducted from the harvested biomass. The harvested biomass is affected by the number of fishes and their sizes. The number of fishes is affected by survival rate where there is a losses percentage due to death (injuries), infection, and escaping. While, the size of the fish is affected by the physical and metabolic performance. The physical and metabolic performance are both affected by environmental conditions, cage conditions, and feeding regimes and rates. Therefore, income has a clear relationship with fish growth which is also related to the feeding pattern. However, there are influencing factors that might reinforce or dilute the fish growth.

The operating cost for any offshore fish farm is a summation of feeding cost, energy consumption cost, net exchange and cleaning cost, fish treatment cost, maintenance cost, and salaries. Among these cost categories, the treatment and maintenance are considered as the most variable ones. Feeding, energy consumption, net services are predictable activities and almost scheduled with some variation due to weather and environmental conditions (eating rate, swimming and physical activity rate, bio-fouling rate). Treatment events are stochastic events that depend on the probability of infection and spreading rate. Maintenance visits are also stochastic events that rely on the probability of failure (structures, cage, mooring, pipes, equipment). Failures depend on accumulated stresses and material strength. Therefore, cost categories have a clear relationship with the environmental loads and conditions that might increase or decrease their levels (frequency and consequences).

3. Context and content modelling of Offshore Fish farming

The context of offshore fish farming is vital to understand the external influencing factors on an entire offshore fish farm, and how internal systems of the offshore fish farming interact with each other (interfaces and feedbacks). Offshore fish farming context can be decomposed into five systems related to the main five processes mentioned in [7]. Context analysis using N^2 interface diagram is an effective method to illustrate interfaces and feedbacks between these five systems, as shown in the diagonal blocks in Figure 1. Moreover, the interface diagram shows the external inputs (Zone 1) for each system, outcomes (Zone 2), interfaces (Zone 3) and feed-backs (Zone 4) with other systems. To fill the interface diagram, the behaviour of these systems and their interactions with each other shall be explored with the help of literature, as in the following subsections.

3.1. Site ecosystem and environmental loading

First, the site ecosystem and loads mainly affect the fish. Oppedal et al., [23] defined several environmental variables that primarily affect the fish as follows: temperature, salinity, dissolved oxygen, water currents, light, and chemical treatments. Spatial conditions such as diseases organisms, parasites, water exchange (e.g. effect of freshwater runoff), pollution are significantly crucial for fish welfare [44]. These environmental variables are highly depending on depth, space and time (seasons). Each fish type has preferable, related physiological structures and metabolic needs, ranges and combinations of these environmental variables. The environmental variables, together with feed and threats sources, influence the fish responses to determine the location

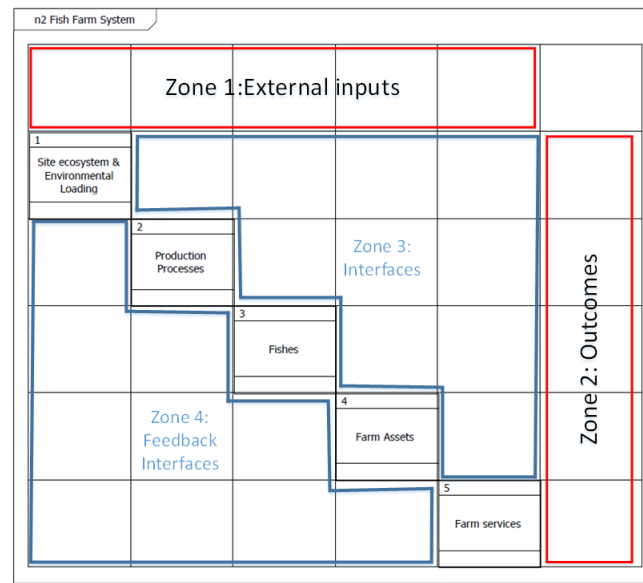


Figure 1. N^2 interface diagram of Offshore Fish farming

(depth), density and swimming pattern to survive. Temperature affects the fish metabolic processes such as circulation, food intake, digestion, growth, bio-energetical re-acclimation and scope of activities [23]. Johansson et al., [9] observed that the preferred temperature range of Salmon was 16 – 18°C within a range of 11 – 20°C. Oppedal et al., [23] highlighted that there is a potential influence of current velocities of strong currents on schooling structure, swimming speeds, directions and depth, even though we have a limited understanding about that.

Second, the site ecosystem and loads mainly affect the farm asset. Toffoli and Bitner-Gregersen [42] have summarised types of ocean waves based on frequency and period of the wave: Capillary, Ultra-gravity, gravity (wind sea, swell), infra-gravity, long-period, ordinary tidal and trans-tidal waves. Depending on the offshore fish farm location, different types of ocean waves might influence its structure, stability, and the cultured organisms inside. Salinity and water currents, shelter (waves), fouling, and sea bed conditions have also effect on the farm. The environmental loading of specific fish farm site influences the fish farm structures (stability, cage deformation, storms, deterioration). Moreover, biofouling, species richness initially increased with depth, but decreased after 1520 m. Species richness decreased significantly with increasing distance from shore [38]. Third, the site conditions over seasons also affect production and service operations in terms of delays and shifting schedules. The harsh weather conditions of offshore sites might cause lack of access-ability for some service operations or more costly operations to due to the longer time for such operations to be accomplished (e.g. Mean time to repair) or due to the need for special equipment and tools. Fourth, the fish faeces, uneaten food, escaped fishes and chemicals/antibiotics have accumulated effect on the site environment [41]. It hard yet to quantify the impact of fish faeces and uneaten food on the water quality of the open sea, but fish escape is a very critical measure that shall be considered and assesses for each fish farming concept.

3.2. Production Process

The production process is a combination of several functions to produce the market-size fishes. It includes smolts-migration, feeding, maintaining (e.g. dead-fish removal, not repair and replace), and harvesting. Feeding process can be decomposed into sub-functions: supply, store, power

supply, feed and control. We have considered the daily services as part of the production process. Whereas other medium or low-frequent services are regarded as farm services, as it is outsourced for many fish farms. The production process is affecting fish growth and welfare. However, the fish behaviour might also affect the production process, e.g. feeding rate/regimes and time-to-harvest.

The feeding process has a reinforcement relationship with the fish growth process. The daily feed is affected by the fish size/weight, water temperature, available oxygen in the water, and feeding policy [17]. The feeding regimes and rates are well defined and controlled either by automatic feeder or manual feeding. In general, each kilogram of salmon requires approximately 1.2 kilograms of fish feed. In its total lifespan, a salmon will, therefore, consume 6-7 kilograms of fish feed [39]. Jørgensen and Jobling [19] have studied the feeding rates (food intake per hour) during night and day, feeding modes under different light conditions and the effects of the length of the daily feeding period on growth for Atlantic salmon. Feeding Time has also effect on the growth, survival, and food conversion ratio. The production is also affected by the fish death rate where dead-fishes are pumped and removed in a daily bases. Moreover, the output is affected by infection and escaping events once they occur.

3.3. Fishes: Growth and welfare

Hamza et al., [17] described the life stages of farmed salmon as eggs, fry, and smolts, adults and harvesting. First three stages are at the freshwater phase, and the remaining three are an at-sea phase. Fishes eat food to gain energy to swim and to grow. Fishes dissipate energy and produce waste. Fishes need oxygen and can live in a specific interval of water temperature and current velocity. Fishes need space to swim in individual and group patterns. Fishes as a living body might get diseases or injuries (hitting the cage wall, net, or each other).

First, *the growth rate is directly affected by the feeding rate, farming conditions (dissolved oxygen, Temperature)*. AKVA [12] illustrated the relations between daily growth (in gram) and available oxygen in water and temperature. The curve shows that salmon can gain 8-9 grams per day when the required amount of oxygen is available, and the temperature range is between 10 – 16°C. The von Bertalanffy growth curve is a more generic model used to estimate growth over time. The growth curve is modelled as a C-shaped curve and depends on growth coefficient, which should be determined for a specific farming condition. There are other fish growth models as Gompertz, inverse logistic, and Schnute models. Føre et al., [11] modelled the growth performance and feeding behaviour of Atlantic salmon (*Salmo salar* L.) in sea cages.

Second, the growth of Atlantic salmon may be affected by *cage space, current speed and fish density* cage space, current speed and fish density even while the temperature, light and feeding regimes are stable. These factors affect the physical behaviour and food conversion ratio. Johansson et al., [9] studied the swimming patterns of farmed salmon under low and high water current velocities. It is expected that fishes will swim faster (speeds of 0.3-0.9 Body Length s^{-1}) and spend more energy to speed up (double, 2 X 0.7 Body Length s^{-1}) and maintain the group structure. However, it was observed that fish experience new swimming pattern during high water current velocities to save energy. Thus, this indicates a shift from circular schooling pattern to stationary swimming against the current in a group. Moreover, the swimming depth for sea trout *Salmo Trutta* in fjord areas is observed to be influenced by habitat, time (day and season), water temperature and body length at the time of tagging [41]. High current velocities might injure the fishes as the probability of collisions with each other and the cage wall increases. This also increases their physical activities and food conversion ratio (probably more feed and lower growth rate).

Third, *disease and treatment process* is a vital issue that shall be considered as it affects the overall production and costs. Fish suffer from diseases and parasites. Hamze et la., [17] used system dynamics simulation, and Alaliyat and Yndestad [15] used agent-based simulation to

predict the impact of diseases within fish farms. It is expected that disease problems to be much lower for farming offshore, compared to in-land or near-shore aquaculture. However, there is limited knowledge of the probability of diseases and parasites for offshore farmed fish.

3.4. Farm asset

As mentioned early in the introduction, there are many contributions and studies of a structural assessment of near-shore fish farms and mostly for high-density polyethylene (HDPE) cages. The HDPE cages are preferable as Cardia and Lovatelli [44] highlighted "due to its limited investment capital, the relative simplicity in the performance of the various farming operations, versatility of the materials used." However, the existing offshore fish farming concepts have a steel structure, e.g. Ocean farm 1 and HavFarm. Even though the offshore oil and gas industry and maritime industry have long and robust experience in designing and assessing offshore structures, the failures might occur, and maintenance is needed, which in total affect the operation and maintenance cost and income losses. Human errors are also important to be considered, for example, the Ocean Farm 1 structure was bent due to water coming in through a hatch in a tank system, and human error was reported in [45] "The closure was opened for inspection the day before and by mistake had been left open". Therefore, it is vital to consider the potential failures, human errors and maintenance events over the farm lifetime in any cost-benefit studies. The failures might occur for any physical asset within the fish farm which generally consists of several sub-systems: (1) Steel structures, (2) Cage/net system, (3) Mooring and anchoring system, (4) Environmental control system (Fish escape control, chemical and waste dispersion mechanisms), (5) Feeding system (Automatic feeder, Barge), (6) Support system (treatment, dead fish collection, vessel support), and (7) Monitoring system (Video, Audio, structural health monitoring).

The first issue related to farm structure is *stability of Offshore fish farm*. Therefore, there are several studies to understand how stable and environmental compatible are the offshore farm structures. Most of the Offshore installations are well designed to withstand and be stable during extreme conditions. However, the instability situations might happen as a combination of technical and human interactions as happened for Ocean Farm 1 case, reported in [45]. Such a situation lead to economic losses (Maintenance cost, capture fishes, etc.). As the purpose of our analysis to conceptualise a simulation model, it is important to consider the impact of potential instability situations. The role of Mooring is to hold cages against the forces generated by wind current and waves and to avoid the transfer of excessive forces (static, i.e. gravity, buoyancy and dynamic, i.e. currents, winds and wave reaction) to the cages [46]. Thus, the incident forces that are act on the mooring lines and anchors shall be quantified.

The second issue related to farm asset is the *structures deterioration process*. Environmental loading exposed to Offshore installations causes cyclic stress variations in its structural members. These stresses accumulate over a lifetime and cause fatigue damages in these members. For example, a wave loading over a 20 years service life will result in about 10^8 cycles of stress variation [47]. Etube [48] illustrates the sea-state probability model to predict crack growth in high strength steel (SE702). This model is based on Gumbel distribution, which is accurately describing the distribution of significant wave height at North sea. Thus, the sea-state equivalent stresses can be accumulated to predict the crack growth and then the time between failures can be determined and used for maintenance cost estimation.

The third issue related to farm asset is the *cage deformation*. Kumar and Karnatak [49] highlighted that "the water exchange inside the cage is inversely proportional to the volume of the net and depends on the speed of the current and the distance between the opposite walls". Therefore, the cage deformation due to currents affects the water exchange and the level of dissolved oxygen. Bi et al., [50] estimated the flow velocity around the fish farm and the effects of cage height, current type (constant and tidal), incidence angle current and level of bio-fouling

on the net.

The fourth issue related to farm asset is the *bio-fouling and cleaning process*. When artificial assets are submerged in the sea, the benthic organisms might accumulate on the asset surfaces, which is named bio-fouling. Bio-fouling is a process that is influenced temperature, salinity, water quality, depth, current and distance to shore. Bi et al., [50] listed four impacts of bio-fouling: (1) increase the disease risk, (2) increase structural failure risk due to hydrodynamic forces acting on the net, drastically affects the coefficient of drag (3) increase the net damage risk and escaped fish, with large cages the losses are greater if the net is torn accidentally [51] and (4) increase the decrease the water exchange and oxygen supply inside the cage. Bi et al., [50] studied and shown the effect of level of bio-fouling on the net. The offshore industry has long experience of bio-fouling and how to estimate the formation and accumulation of biofouling communities on steel structures [38].

3.5. Farm Services

The farm services are affected by the production and maintenance operations, e.g. repair, bio-fouling removal, diseases treatment, net exchange. Besides, routine maintenance and certain management activities such as net exchange or fish sorting can become more complicated for large and offshore cages [51].

4. Conclusions

In the previous section, we tried to explore the interfaces between the interacted systems that are within any offshore fish farming context. These interfaces are compiled and illustrated in Figure 2. Moreover, we tried as much as possible to explain the quantify relationships of these interfaces. The impact of some interfaces are quantified by well-known formula in literature, and some need further studies. Furthermore, the context analysis and the interfaces clearly show the influence of the farming concept [40], [52] and design parameters [53], [49] on total farm income and costs. It also helps to determine the critical acceptance criteria to evaluate offshore fish farming concepts. Capacity and capital cost is vital criteria, e.g. ocean Farm 1 has the capacity of 1.5 million salmon, and it is a 300 million US\$ project and includes 61 meter high (approx. 40 meters in seawater) by 91-meter diameter [54]. The mesh-wire frames and nets are designed to disperse wastes and support higher fish packing density [54]. It becomes clear based on the context analysis that farming concept is also responsible for providing the right welfare environment for fishes to grow, even though the growth process is related to feeding and metabolic processes.

The farming concepts must enable the fish to get the required water exchange and prevent high current velocities from being exposed directly to the fishes. The farming concept shall be proactive by design-out potential failures, predictive to detect unexpected failures, easy to be maintained and preventive for bio-fouling communities. These design requirements aim to cut-off the maintenance cost. One of the most critical criteria is the escaped fish rate. There is a Norwegian Standard 9415 for cage farming equipment to prevent fish escape. However, farming concepts might differ in their mechanism to avoid or mitigate any escaping events.

It is worth to highlight that at the moment and due to limited experience with offshore fish farming, there are several relationships between these dynamic process not quantified, i.e. not an explicit equation, and several behaviours and influencing parameters are still unknown for offshore farming applications.

Therefore, it is the time to conceptualise a valid profitability model for offshore fish farming and determine which influencing factors and impact relationships shall be studied and measured. Then, it might be possible to develop an integrated simulation model with valid and reliable outcomes.

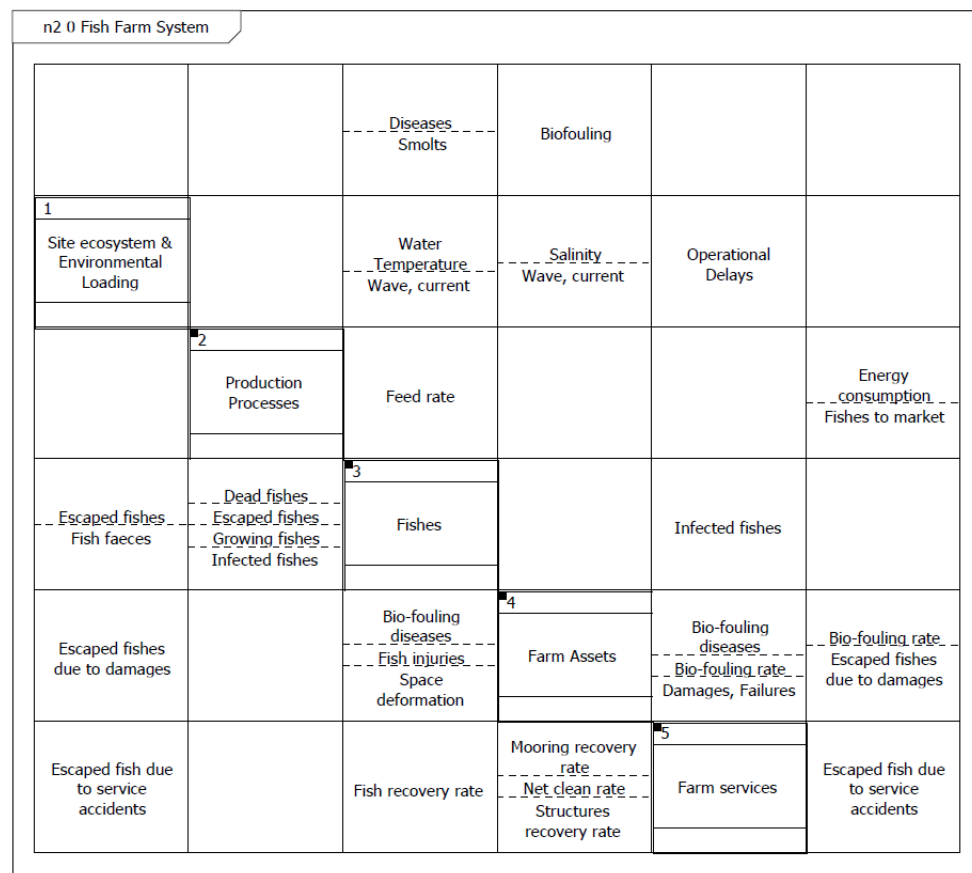


Figure 2. N^2 interface diagram of Offshore Fish farming

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