33rd European Modeling & Simulation Symposium
18th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 ISBN 978-88-85741-57-7 © 2021 The Authors.
doi: 10.46354/i3m.2021.emss.034

A Digital Twin of Intensive Aquabiotechnological Production Based on a Closed Ecosystem Modeling & Simulation

Mikhail Zhabitskii[1,*], Yuriy Andrienko[1], Vladimir Malyshev[2], Svetlana Chuykova[2] and Aleksey Zhosanov[2]

[1] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31, Kashirskoe shosse, Moscow, 115409, Russia
[2]Second Institution, Full Address, City, Postcode, Country JSC "Paninskoe", Panino 1, Medvenskiy district, Kursk region, 307032, Russia

[*]Corresponding author. Email address: jabitsky@mail.ru

Abstract

Currently, intensive fish farming using closed water circulation technology is becoming one of the breakthrough technologies in the aquaculture production. Digital transformation for such production is necessary for the effective management of ultra-high-density aquaculture farms. This transformation is based on the digital twin of aqua-biotechnological farms. The authors performed digital modeling & simulation of the biotechnological component of intensive aqua farm. The main equations of the model are presented in the article. Models of lungfish and trout ecosystems are considered. The models were tested as part of the digital twin for the real aqua farm. The qualitative coincidence of the results of modeling & simulation with the behavior of the ecosystem is obtained. The model has not yet achieved sufficient accuracy for commercial use. The reasons for the insufficient accuracy of the simulation are discussed. Some variants of the simulation model's development for simple closed aquatic ecosystems with a large biological load are considered. It is concluded that it is necessary to integrate a digital twin based on a simulation model of a biosystem with the technology of the Industrial Internet of Things to achieve the necessary accuracy of describing a complex engineering and biotechnological system.

Keywords: Modeling & simulation, Closed water circulation technology, Digital twin, Industrial Internet of Things.

1. Introduction

Following the fourth industrial revolution ideas and technologies the active transformations in various industry branches are taking place. The main direction of many such transformations is based on the digital twin creation for production and business. This approach makes it possible to significantly increase the industrial and technological system's productivity by adequately predicting their behavior under the control action. The digital twins make it possible to indicate the optimal algorithms for the industrial systems functioning without natural tests and real experiments. This may reduce the costs of working out technological modes and predicting the consequences of modernization and reconstruction of almost any engineering facility. However, the digital twin structure is different for different engineering object types and different life cycle stages. In this paper, we discuss biotechnological engineering production. It is one of the most interesting production types for imitation modeling. The most important distinguishing feature of such systems is their continuous self-development process. Such a process is based on the own characteristics and parameters of biological components. At the same time, biological processes are related to the physical and chemical parameters of the engineering systems in which they are embedded. The exchange of matter and energy between biological components, engineering devices, and the external environment takes place during the engineering and biotechnological complexes operation. Unlike a purely technical system, a biotechnological system cannot be turned off. The processes of development, the exchange of matter and energy, as well as the processes of degradation will occur at a significant level for any overall system states, even in the absence of influences from the technical component. Thus, complex biotechnological systems modeling requires a specific approach. In this paper, we present a constructing heterogeneous digital modeling methodology for the biotechnological systems functioning analysis. The purpose of the further operation of digital twins based on such models is to optimize their operating modes for solving production problems. Similar approaches are described in references.

2. Materials and Methods

2.1. Modeling & simulation object

In this section, we will describe the simulated system, the main patterns considered and the mathematical apparatus of modeling.

Within the framework of this study, the object of modeling is a technological closed ecosystem for commercial fish products cultivation. The real aquafarm Paninskoe in the Kursk region of the Russian Federation was chosen as a reference model. General parameters of the modeled object are:

Charmouth fish (also known as mudfish or Clarias anguillaris) is grown as the main product.

Annual production volume is 300-350 tons of fish products per year.

The total volume of fish tanks is 500 m3.

The volume share of fish products in cages is up to 50%;

The standard technological cycle duration is 9 months.

The selected subsystems can be divided into 2 types. These types are engineering subsystems and biological subsystems. In addition, for aquafarms, the most important component is such a specific subsystem as the aquatic habitat of aquaculture. It is the water environment that is the mediator through which the interaction between the engineering and biotechnological components of the complex understudy is carried out. Two main biological subsystems can be distinguished for closed water circulation aquafarms with systems of biological purification of the aquatic environment. The first is the commercial aquaculture population. For purposes of this research, a commercial herd of the charmouth fish breed was selected. In this work, only the commercial fish population was subjected to detailed simulation modeling. The dynamics of the bio-purification system organisms' development has not been studied and is not modeled. Thus, the biofilter in the framework of this work can be considered as a component of the engineering subsystem.

The engineering subsystem within framework of this study was considered as a tool of controlling influence, influencing the habitat parameters and the processes of fish population life activity. The engineering subsystems of the digital twin include some different parts.

An aquatic environment circulation system provides a set exchange level in fish tanks. From the experience of operation, it is known that for mono-population ecosystems with a high fish density (up to 50%), the circulation rate should ensure the exchange of the aquatic environment at least once per hour. The circulation mode is provided by circulation pumps. Two circulation pumps groups are installed in the circulation circuit. One provides injection into fish-breeding tanks, the other one injects into the water treatment system. These two sections of the circulation circuit are separated by buffer leveling basins.

2.2. Simulated processes

From the point of view of simulation modeling of the circulation of the aquatic environment, which determines the biological systems behavior, this is enough to describe pumps by a single parameter, such as outgoing flows. Other parameters such as pressure, electrical voltage, amperage, and others are important for modeling the engineering subsystem description but do not affect aquaculture development. The circulation rate influence mechanism at the biological system is the biological processes suppression due to fish poisoning with vital activity products water dissolved. The rate of formation of ammonia nitrogen for the specified planting densities is such that dangerous concentrations are reached within about an hour.

The heating-cooling system regulates the aquaculture aquatic habitat temperature. For different fish types, the optimal temperature parameters vary greatly. So, the optimal temperature is 28-30 degrees Celsius for the charmouth fish breeding and growing. When the temperature decreases, the fish development rate decreases sharply. The fish population death begins while water cooling below 20 degrees Celsius. When the temperature rises above the optimal temperature, the growth rate of the fish also decreases.

For freshwater trout, the temperature conditions are completely different. The temperature optimum is 13-14 degrees Celsius, and mass death occurs when the temperature exceeds 20 degrees Celsius. In this work, the thermal balance in the circulation system was modeled to maintain optimal temperatures. The heat source is a heat exchange pool with submersible heat exchangers with a heat transfer fluid temperature of 60 degrees Celsius. The temperature of the coolant after heat exchange is 40 degrees Celsius. The heat transfer models were calculated based on experimentally measured values of the coolant fluxes and the specified temperature drop. In practice, there is a seasonal temperature difference in the production room. The temperature ranges from 18 to 25 degrees Celsius. In this study, computational modeling of the heat transfer processes and heat exchange between the heating circuit, the water environment, and the air environment was not performed. We used empirical dependences obtained by direct measurement for all media temperatures, as well as the value of the heat transfer fluid flow.

For many aquaculture types, oxygen water saturation is essential. However, this is not essential for the charmouth fish breed. Charmouth fish is a lungfish. So, it compensates for the oxygen lack in the water by air-breathing.

The most important external parameter that determines the biological population growth rate is feed intake. Feeding modes have many parameters that affect the weight gain of farmed animals. These parameters include the composition of the feed (a complex parameter), its dispersion, the feed supply mode in aquariums, the time of decomposition of the feed in the water, the feed distribution uniformity over the reservoir surface. In this study, a simplified model was used, assuming that the growth of organisms is affected only by the amount of feed received, but not its composition. Of course, the dependence on the temperature and fish habitat impurity was also considered. The correlation coefficients for these dependencies were taken empirically measured for the reference fish populations.

Within the real production, there is a plural number of fish-breeding tanks. Planting of fish-breeding material occurs sequentially, with a time delay of arbitrary duration. At the reference enterprise, more than 60 fish-breeding tanks are used for this purpose. The release of fish tanks occurs as the full-size commercial products are caught. After that, a new production cycle begins. The biomaterial starting seating is made with a sufficiently low density. As the aquaculture critical density is reached, the excess population is transplanted to free tanks. This process should be managed based on population control data and objective decision-making criteria. One of the unsolved complex problems that require the use of digital doubles is the solution of the predictive problem of complex optimal use of existing aquariums for fish breeding for a long period. This problem is solved by including a digital simulation model of fish population growth depending on control actions into a digital twin. Controlling effects on the biological system are carried out by regulating the parameters of the aquatic habitat and feeding regimes. A market model with a forecast of demand peaks in terms of volume and price will be added to the commercial aquaculture breeding and growth model considered in this study at future. This step is important to take, because the end user is interested in managing the economic efficiency of the company based on high-quality forecasts.

Within the framework of the general simulation model, engineering systems in this work were used as control factors for modeling the development of the biological subsystem of fish-breeding tanks. Description of the behavior models of engineering equipment both as a tool for influencing the biotechnological system, and from the point of view of reliability analysis and cost management of operation is an interesting task. However, these issues are not considered in the framework of this work.

2.3. Equations and mathematical model

The mathematical model which was used to describe the processes of ecosystem development in a separate fish-breeding tank will be described in more details below. The initial conditions are data on the starting composition and parameters of the ecosystem. There is no preface for this idea. There are only three parameters for the basic model: the size of the individual in the population, the number of individuals in the tank, and the type of aquaculture. In the basic model, the size of all individuals is considered the same. In production, this is ensured by pre-sorting the fish-planting material. There is a certain variance in the size of individual fishes, and this will be considered in future works. The same size of individuals in the tank is important to avoid cannibalism of the population. Therefore, tracking and leveling the size spread in the industrial production of aquaculture is an element of technology.

A system of ordinary differential equations was used for modeling. These equations describe the balances of the essential parameters of the population and the habitat that are under the influence of engineering systems. The phase trajectories in the solution space are determined both by the properties of the system and by the scenarios of changes in these controlled influences. The external control effects of engineering systems on the environment and biological organisms can change in accordance with various scenarios. These scenarios described different levels of optimality of compliance with technological regimes. In particular, the scenarios of technological risks are considered. The risks in this context are accidents, poor management of technological modes, lack of resources, or their late delivery.

The model used included five ordinary differential equations describing the dynamics of the system parameters. Differential equations describe the temperature of the aquatic environment, the concentration of dissolved molecular oxygen, the integral concentration of pollutants in any form of a nitrogenous compound, such as ammonium or nitrate, the mass of a single sample of farmed fish, the number of fish in each fish tank. The final equation is an algebraic equation for the constancy of the total volume of the fish-breeding capacity, consisting of the volume of aquaculture and the volume of the aquatic environment.

The first equations has the form:

$$c\frac{dT}{dt} = -Q_1 - Q_2 + Q_3 - Q_4 + Q_5 \tag{1}$$

This is the heat balance equation. Here T is the temperature of the water in the pool, c is the heat capacity of the pool, Q_1 is the heat loss through the tank walls, Q_2 is the heat loss through the water surface, including evaporation, Q_3 is the heat release of living organisms, Q_4 is the arrival of heat energy when the tank is filled, Q_5 is the entrainment of heat energy when the liquid is drained from the pool. If the temperature of the filling water is higher than when draining – the temperature in the pool is higher than in the Paniskoe aquafarm breed thermophilic fish, such as charmouth fish now. Fish growth accelerates exponentially with temperature increasing. At the same time, expensive fuel is consumed for heating the water. We need to raise the water temperature to accelerate the growth of fish, but this increases fuel costs. From this contradiction, the most effective temperature regime is formed. Trout need cold water to maintain the solubility of oxygen. At the same time, the law of intensification of growth with temperature is preserved. Here, the optimum is achieved due to conflicting temperature requirements to ensure a balance between the growth rate of the fish and the oxygen saturation of the habitat. The optimal water temperature in this case is lower than the temperature in the production premises. The trout's habitat is cooled by mixing cold artesian water. This is also a paid resource, and the point of economic optimum depends on three parameters.

$$\frac{dM[O_2]}{dt} = -\Delta M[O_2]_1 - \Delta M[O_2]_2 + \Delta M[O_2]_3 - \Delta M[O_2]_4 \tag{2}$$

This is equation of the dissolved oxygen balance. Here $M[O_2]$ is the mass of oxygen dissolved in the tank, $\Delta M[O_2]_1$ is the loss of oxygen through the water surface, $\Delta M[O_2]_2$ is the oxygen consumption by the fish, $\Delta M[O_2]_3$ is the oxygen supply by the flowing water, $\Delta M[O_2]_4$ is the oxygen supply by the flowing water. For trout, an oxygen saturation regime of up to 300% is created in the flowing water. For this purpose, evaporating liquid oxygen and a special device for saturating water with oxygen are used. For lungfish, control of dissolved oxygen is not required, and that equation can be excluded from the model.

$$\frac{dM[N]}{dt} = \Delta M[N]_1 + \Delta M[N]_2 - \Delta M[N]_3 + \Delta M[N]_4 \tag{3}$$

This is pollution balance equation. This equation describes the balance of biological contaminants in a fish tank. As a measure of pollution, the total concentration of ammonium and nitrate nitrogen was considered. Nitrogen-containing pollutants are released by aquaculture during vital activity, as well as during the decomposition of feed residues. At ultra-high planting densities (up to 50% for carmouth fish and up to 30% for trout), critical concentrations are created in a very short time. Such an aquatic habitat requires intensive cleaning within a closed water circulation. Water regeneration takes place on biofilters. The incoming flow is cleared of contamination, although not completely. Notation in the equation: $M[N]$ - the mass of ammonium and nitrate nitrogen in the tank, $\Delta M[N]_1$-the release of ammonium and nitrate nitrogen by fish, $\Delta M[N]_2$ – the release of ammonium and nitrate nitrogen by feed, $\Delta M[N]_3$ – the removal of ammonium and nitrate nitrogen by runoff from the pool, $\Delta M[N]_4$ – the introduction of ammonium and nitrate nitrogen by water into the pool.

$$\frac{dM}{dt} = \Delta M \tag{4}$$

This is the equation of the balance of the average individual size in the population. Here M is the mass of one individual, ΔM is the instantaneous rate of its change at the local value of the system parameters. Despite the simplest form of the right-hand side in a collapsed form, it is the most non-trivial equation. Habitat parameters are the total space of habitat parameters (temperature, pollution, oxygen saturation, illumination), feed characteristics, as well as population parameters (size, life cycle stage, heredity). As will be discussed below, it is the complexity and difficulty for the ΔM approximation in the entire phase space of the essential parameters that is the key uncertainty for the model under consideration.

$$\frac{dN}{dt} = -\Delta N_1 + \Delta N_2 - \Delta N_3 \tag{5}$$

This is equation of population size change. N is the number of individuals in the tank, ΔN_1 is the number of individuals caught, $\Delta N_2$is the number of individuals planted, ΔN_3 is the number of dead individuals per unit of time. The change in the number of individuals due to catching and replanting occurs simultaneously with the development of the population. The corresponding specific functions are the delta functions. The specific rate of death is a smooth function that depends on the aquaculture living conditions.

$$V_1 + V_2 = V_0 = const \tag{6}$$

This is the law of conservation of volume. Here V_1 is the total fish volume, V_2 is the water volume. At high and ultra-high planting densities in closed ecosystems, the volume of fish should not be neglected.

Note that the dissolved molecular oxygen concentration is not essential for all fish breeds. For trout, for example, this parameter is critical. For lungfish, this equation can be excluded from the simulation, since the dissolved molecular oxygen concentration does not affect the growth and survival of these breeds.

This simulation model of a single-species ecosystem has several characteristic times. The smallest of these is the time of change in the concentration of molecular dissolved oxygen. It's only a few minutes for some fish species. This corresponds to the rate of water exchange up to 10 times per hour. The next characteristic time of the biological process is the time of aquatic environment pollution by the products of the biological organisms' vital activity. This is a typical time - about 1 hour. In addition, there are feeding cycles with several hours of characteristic time. Finally, the aquaculture cultivation total cycle was considered in the range from nine to twenty months. Thus, we have a rigid system of differential equations with a difference in the characteristic times of the processes up to 8-9 orders of magnitude. This made demands on the algorithms used to numerically solve the system.

3. Results

The result of the work is currently a system for simulating the fish population growth from the initial size of 50-100 grams to the commodity size of 1-2 kilograms. The total time of the simulated process is 9-24 months. The coefficients of the first approximation and the dependencies in the equations were estimated from open-source data. However, comparison with the behavior of real populations in real production led to the need to change almost all the initial dependencies. This may be due to that many of the aquaculture habitat parameters optimized for industrial production are not present in the natural habitat. To date, the adequacy of the model for the output parameters at the level of error of 15-20% compared to the population parameters dynamics of the real productive fish tanks have been achieved. At the same time, the spread of experimental data between populations in parallel aquariums is about 8%. We have chosen two values as integral parameters of predictive modeling. The first is the mass of the population of commercial fish grown on a reference cycle of nine months. The second is the specific feed consumption per unit mass of marketable products.

Currently, our calculations were performed mainly for the cultivation of charmouth fish. Only trial calculations were carried out for freshwater trout. This is since the reference aquafarm specializes in charmouth fish production. Freshwater trout cultivation is at the stage of basic biotechnology development. Therefore, experimental data for trout population qualitative modeling is not enough. In addition, the trout population dynamics simulation model is more complex and sophisticated. This is caused by a more complex system of relationships in the system, considering the modeling of oxygen solubility. In addition, the properties of the mathematical model are more difficult. It is necessary to calculate the most rapid physical, chemical, and biological processes, changes in the dissolved molecular oxygen concentration in the aquatic environment.

Significant discrepancies between predictive modeling data and real ecosystem behavior require further discussion and understanding. Since the goal of the work is not just a scientific result, but a technological tool for the production process managing for a commercial enterprise, the accuracy of the prediction obtained so far is insufficient The reasons for the deviations of the experimentally observed population development from the simulation model's predictions have been discussed. They can be divided into three groups. Three areas of compensatory measures to achieve the study target result can be distinguished.

First, there are defects in the digital simulation model. This is partly due to the lack of experimental data on the behavior of the simulated object for description in all modes and stages. The dependence coefficients in the modeling equations were refined empirically. In general, the coefficients of the dependence of biological processes on external conditions are not constant in different regions of the phase space of the variables that characterize the system. In–the case study, there are no analytical dependencies or detailed tables of dependencies on various variables of the aquaculture habitat and development stage in the literature. There is a strong possibility that further refinement of the model requires more detailed experimental data to better coefficients approximation for different phase-space regions.

In addition, up to the full production automation point and ensuring continuous parameters monitoring, the real-life aquaculture cycle scenarios and simulation may differ. But now Paninskoe aquafarm have no full production automation yet. Currently, the control of growing conditions is provided only three times a day. At the same time, significant intra-day fluctuations in the parameters of the aquaculture aquatic habitat are possible between the control points. Similar deviations from the model parameters can be observed in feed feeding modes.

There are also fundamental limitations on the achieved accuracy of the model. The experiment shows that initially similar populations developing in the same conditions (neighboring basins) may differ in weight gain by up to 8%. Despite the relatively large statistics of organisms in one pool (two to four thousand individuals), the population's biological processes are not strictly deterministic. Thus, there are limitations on the model's predictive accuracy. Certainly, it cannot be higher than the variance of the real population's characteristics. In general, result correlate with the data of other publications, such as R. Ismail and others.

4. Conclusion

In the following part of this paper the main conclusions of the work done and the directions for further research are described.

In the course of this work, a simulation model was constructed for the biological system development for monoid fish populations in an artificial engineering-controlled environment. The purpose was to create a digital twin of an industrial aquafarm for efficient production processes optimization. It is actual task, and our approaches are consistent with the conclusions of the other authors The accuracy of the simulation is currently insufficient to implement the model as a production management tool. However, the manufacturer is planning a production digital transformation based on the Industrial Internet of Things technology in 2021-2022. This will ensure continuous digital monitoring for the engineering systems parameters, the environment, the aquaculture aquatic habitat, and the dynamics of the fish population development parameters. Providing a continuous data stream with high time resolution will allow to qualitatively improve the model accuracy. These works are planned for 2022. The aim of the research is the creation of a digital product for predictive analytics and management decision support in the operation of industrial fish farms with high-intensive closed ecosystems. After testing at the reference aquafarm data, the product can be presented on the market of high-tech solutions for intensive fish production products using closed water circulation technology.

References

Carius, L., Pohlodek, J., Morabito, B., Franz, A., Mangold, M., Findeisen, R., Kienle, A. (2018) Model-based State Estimation Based on Hybrid Cybernetic Models *IFAC-PapersOnLine*, 51 (18), pp. 197-2023

Fore, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J.A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A., Sunde, L.M., Schellewald, C., Skoien, K.R., Alver, M.O., Berckmans, D. (2018) Precision fish farming: A new framework to improve production in aquaculture *Biosystems Engineering*, 173, pp. 176-193

Ismail, R., Shafinah, K., Latif, K. A (2020) Proposed Model of Fishpond Water Quality Measurement and Monitoring System based on Internet of Things (IoT) *IOP Conference Series: Earth and Environmental Science*, 494 (1), paper № 12016

Lagasco, F., Collu, M., Mariotti, A., Safier, E., Arena, F., Atack, T., Brizzi, G., Tett, P., Santoro, A., Bourdier, S., Salcedo Fernandez, F., Muggiasca, S., Larrea, I. (2019) New engineering approach for the development and demonstration of a multi-purpose platform for the blue growth economy. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering* - OMAE, 6

Mahalik, N.G.P.C., Kim, K. (2014) Retrofitting high-tech systems in land-based aquaculture to improve production efficiency: An Automated expert system architecture *IETE Technical Review (Institution of Electronics and Telecommunication Engineers, India)*, 31 (2), pp. 153- 161.

Ogorodnikov, P.I., Perunov, V.B., Chirkova, V.Yu. (2012) The influence of human factor on financial sustainability of agricultural production. *Economy of Region*, (2), pp. 232-239

Safin, M.A., Gerasimov, E.I. (2019) Automated process control system for closed water supply installations for fish cultivation. *E3S Web of Conferences*, 124, paper № 05023

Tarkhov, D.A., Malykhina, G.F. (2019) Neural network modeling methods for creating digital twins of real objects *Journal of Physics: Conference Series*, 1236 (1), paper № 012056

Shufen, H., Wei, C., Shuiyin, X. A (2020) LabView-based Smart Aquaculture system. *Journal of Physics: Conference Series*, 1550 (4), paper № 042037

Xiao, J., Zhang, Y. (2020) Marine factory farming techniques and equipment. *IOP Conference Series: Earth and Environmental Science*, 615 (1), paper № 012013

Xu, L.-J., Wang, N., Feng, Y., Bao, D.-N., Jorshin, K. (2014) Design of aquaculture system based on wireless monitoring and its testing. *International Journal of Interactive Mobile Technologies*, 10 (5), pp. 68-73

Zhabitskii, M G, Andryenko, Y A, Malyshev, V N, Chuykova, S V and Zhosanov A A (2021) Digital transformation model based on the digital twin concept for intensive aquaculture production using closed water circulation technology *IOP Conf. Series: Earth and Environmental Science* 723, paper № 032064 doi:10.1088/1755-1315/723/3/032064