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TESTING OF A DYNAMIC SIMULATION MODEL FOR RECIRCULATING AQUACULTURE SYSTEMS TO SUPPORT MANAGERIAL DECISIONS

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ABSTRACT

Economic evaluation for design and operation of Recirculating Aquaculture Systems (RAS) may effectively be supported by an appropriate dynamic simulation model. The complexity of the process requires a detailed analysis, while the experimental work is time consuming and expensive. However, this complexity is manageable for the new modelling methodologies. Accordingly, the problem solving capability can be essentially increased by combining experiments with computational model based studies. Considering the importance of the inherent coupling between structural and functional characteristics in design and control of RAS, Direct Computer Mapping (DCM) of programmable structures has been experimentally implemented for simulation of RAS aquaculture operation by the Research Group on Process Network Engineering in the past year. In the present work, the parameter sensitivity of RAS is studied with the help of the implemented model, using available data for African catfish (Clarias gariepinus) from the literature, as well as from experiments running at NARIC Research Institute for Fisheries and Aquaculture. From model development points of view, various semi-empirical and empirical formulation for weight increase, feed conversion rate, faecal and ammonia excretion, and mortality are applied. To allow further bio-economic calculations, the recent work focuses on the effect of the ratio of freshwater supply and the efficiency of the biofilter on the operation in a given stage of the process. The simulation model enables us to determine the economic impact of these factors.

Keywords: Recirculating Aquaculture Systems (RAS), modelling and simulation, Programmable Structures, economic impact

INTRODUCTION

Aquaculture is one of the fastest growing agri-food sectors globally; the supply of aquaculture products increased from 4.7 million tonnes in 1980 to 76.6 million tonnes in 2010, representing an average annual growth rate of 8.3% (*FAO*, 2017). Although the bulk of the production boom came from traditional pond and cage farming technologies, increased focus on resource efficiency, food safety and the need for programming harvesting schedule has called for the emergence of farming technologies, enabling independence from the external environment and better control of production (*Bostock et al.,* 2010). Due to these sustainability issues, recirculating aquaculture systems (RAS) are in the front of biological and engineering developments, as these systems are highly efficient in terms water use (0.1-1 m^3/kg fish produced, in contrast with traditional pond systems using 5-20 m^3/kg fish), as well as nutrient use and discharge (*Verdegem and Bosma*, 2010; *Sturrock et al.* 2008; *Martins et al.* 2010). RAS are defined as production units that filter and recycle water by removing waste products excreted by the fish. Due to higher automation and more sophisticated machinery, RAS requires larger investment costs and energy costs per unit production, than traditional inland production systems (*Bostock et al.*, 2010, *Sturrock et al.* 2008). On the other hand, the comparative advantages, described above, make RAS technologies viable in a legal-economic environment, where water and nutrient resources are scarce and costly, while environmental regulation strictly applies the "polluter-pay-principle" and poses high discharge fees on farmers. Operating RAS has also advantage in markets that require programmed (e.g. weekly) supply and where high food safety standards prevail. Given this background, RAS industry mostly flourish in water-stressed countries of Western Europe, such as the Netherlands and Denmark, however in certain aquaculture segments (caviar and sturgeon production and fingerling production of high value species) RAS are also used in Central Europe. In order to move forward in commercialisation of this technology, combining biologic and engineering knowledge with economics is needed (*Kazmierczak and Caffey*, 1995; *De Ionno et al.*, 2006).

Considering this background, the objective of this paper was to analyze how engineering performance variables (biomass density; feeding strategy; ratio of freshwater supply and efficiency of the biofilter) impact the profitability of RAS by simulating the operation of a theoretical system, using literature-based quantitative relationships to model the biological and technological subsystems.

METHODS AND APPLIED DATA

Applied modelling and simulation methodology

The basic idea of Direct Computer Mapping (DCM) is that we map the building elements and the structure of process models onto the elements and connections of a computable program code, directly, without their representation in any single, specific mathematical apparatus (*Csukás*, 1998). On the contrary, the individual brief programs can be executed by a cyclically repeated algorithm, similar to an operational system.

The recently used method automatically generates programmable structures for the simulation models from a network structure and from the meta-prototypes of the state and transition elements (*Varga et al.*, 2016b, *Varga et al.*, 2017). In the graphical (GraphML based) model the locally programmable prototypes may be edited from the prototypes. The initialised and parameterised structural model is prepared for the common consideration of "model specific conservation law based" additive measures and of the "over-writable" signals. The general interpreter first generates the case-specific declarative model database, next executes the dynamic simulation. In the applied transition oriented model representation, all of the causally coordinated consequences of the functionalities may be processed together. This feature supports the robust execution of the multiscale models by a general purpose core program. It makes also possible the unified, common generation and execution of the balance-based and the rule-based sub-models.

Recently the methodology has been experimentally implemented for simulation of RAS operation (*Varga et al.,* 2015; *Varga et al.,* 2016a).

Modelled RAS system and implemented data from literature

In the present study the pilot system of the Department of Aquaculture at Kaposvar University was studied to support the preparations for the future experiments planned.

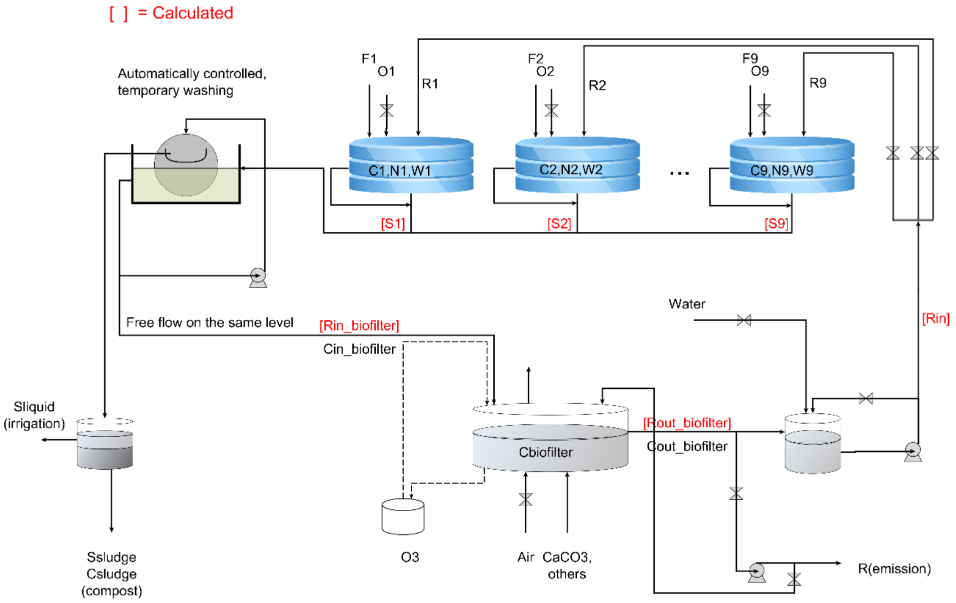
The species selected for modelling was the African catfish due to the fact that the data available for major technological processes, are more abundant compared to other potential species. The calculation formulas were mainly obtained from the description of *Verdegem et al.* (2014) African catfish system, where the empirical relationships were derived by long term production experiments. These empirical relationships cover all the necessary processes to be modelled, such as the increase of body weight, as well as the mortality, the amount of consumed feed, the dry matter content of fish and the protein content of fish body in the percentage of body weight. Regarding the calculation of metabolic waste emission, we utilized the nutrient composition of a widely available and utilized feed Aller Bona Float for African catfish, provided by Aller Aqua (*Aller Aqua*, 2017).

In line with the planned pilot experiments, we modelled a 150 day production period, where fish were expected to grow from 30 g to about 900 g.

The flowsheet of the investigated process is illustrated in *Figure 1*.

Figure 1

The modelled pilot Recirculating Aquaculture System



In the *Figure 1*, blue tanks represent the 3 lines of 3 consecutive production tanks with 0.7 m^3 individual volume. The production tanks can be characterized by the following parameters:

- C1 – C9: dissolved components (e.g. O_2, NH_4, NO_3) and temperature,
- N1 – N9: the number of fish in the tanks,
- W1 – W9: the average weight of fish in the tanks,
- F1 – F9: the supplied feed to the tanks,
- O1 – O9: the supplied O2 to the tanks,
- R1 – R9: the recycled water to the tanks.

From the production tanks, water is forwarded by gravity to the biofilter through a drum filter, where the solid containing sludge is separated. S_{liquid}, S_{sludge} and C_{sludge} represent the liquid and dense phases of sludge components. From the biofilter, the treated water is recycled back with a pump to the fishtank, with the appropriate fresh water supply. $C_{in\_biofilter}$ and $R_{in\_biofilter}$ stands for the components and for the calculated flow that moves from the drum filter to the biofilter, while $C_{out\_biofilter}$ and $R_{out\_biofilter}$ designate the components and flows towards the fish tanks. Most of the parameters in the Figure (written by black letters) can be both measured and calculated, while red coloured parameters in the brackets are unmeasurable, but can be calculated by the model.

RESULTS AND DISCUSSION

Having overviewed the components of the pilot system, we developed the programmable structure of the model in GraphML format (*Figure 2*), in line with the principles of DCM. Model elements of "Fish Tank" and "Life processes of fish" represent the 9 tank pilot system in the model, temporarily parameterized identically. In this graphically editable form, behind the graphical illustration of the model, functionalities (empirical relationships, initial data, etc.) were also added to the structure through the recently applied yEd graph editor.

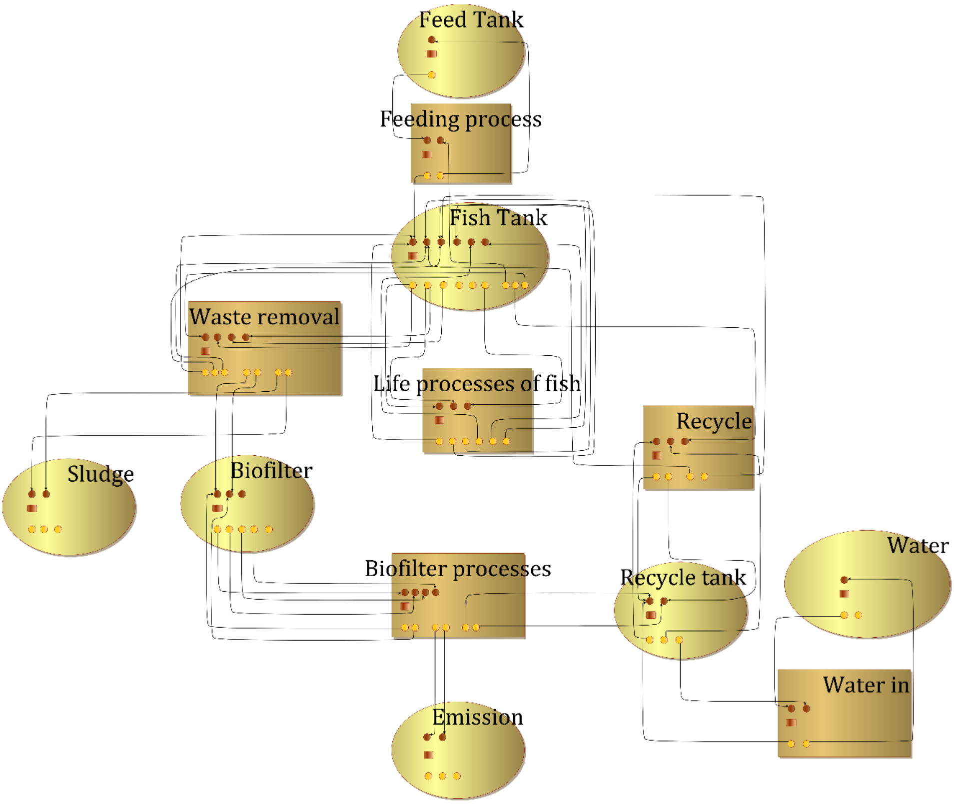
Initial technological parameters of the simulated system are summarized in *Table 1*.

A representative part of simulated results can be illustrated with the following diagrams. *Figure3* shows the changing of stocking density and concentration of feed in fish tank during the 3600 hours of simulation period. It is to be noted that daily feed supply was modeled according to the prescriptions of Aller aqua (*Aller Aqua*, 2017), where 5 feeding stages are suggested in line with the body weight of fish. Considering that these values seemed to be relatively high during the test simulation, we applied a 3 kg/m^3 heuristic limit in the model.

During the simulation we took into account the differentiation of fish, assuming a 10% under-sized and 10% over-sized group amongst the produced fish. Accordingly, *Figure 4* shows the growing of fish during the simulation period. *Figure 5 and 6* show the calculated concentration of various components (O_2, CO_2, HCO_3, NH_4, NO_2, NO_3, COD) and feed components (protein, fat, carbohydrate, ash) in the fish tank during the simulation period.

Figure 2

The programmable structure of the modelled RAS



It is to be noted that these components can be monitored in every time step of the model in each tank shown in of *Figure 1* during the simulation, which can serve as a detailed quantified overview about the technological parameters for economic evaluations.

Considering that in the recently made simulations the quality of the feed, the temperature, the dissolved oxygen level, as well as the quality and quantity of fish were the same, we focused on the effects of water consumption and of excess nutrient discharge. Analysis of the detailed numerical simulation results show that pollution taxes are high but not sensitive to the recently changed system characteristicis, because pollution is more dependent on the production technology, such as on specific feeding rate, feed conversion, oxygen consumption, growth, and mortalities. In contrast, specific cost of water supply is essentially determined by the recirculation rate and water exchange rate chosen by the farm management, as well as by the efficiency of biofilter. The respective calculation results are summarized in *Table 2*.

Table 1

Initial technological parameters of the model

Model elements	Parameters	Value	Unit
Fishtank	Total volume	6.3	m^3
	Water exchange	0.8	tank m^3/hour
	Set temperature	23	°C
	Initial number of undersized stock	100	pc
	Initial average weight of an undersized fish	27	g/pc
	Initial number of normal stock	2700	pc
	Initial average weight of a normal fish	30	g/pc
	Initial number of oversized stock	300	pc
	Initial average weight of an oversized fish	33	g/pc
Feed storage	Initial mass in the storage	10000	kg
	Protein content of feed	0.49	kg/kg
	Fat content of feed	0.12	kg/kg
	Carbohydrate content of feed	0.233	kg/kg
	Ash content of feed	0.077	kg/kg
Feeding process	Prescribed feed level	3	kg/m^3
	Feeding strategy	According to Aller aqua	nd
	Prescribed time step	12	hour
Waste removal	Ratio of non-eaten feed	0	nd
	Ratio of separated solid	0.95	kg/kg
	Specific amount of liquid, used for solid removal in drum filter	30	kg/kg
Biofilter	Ratio of recycling	0.95	nd
	Total volume	4.25	m^3
	Mass of biomedia	573.75	kg
	Biomass	371	kg
	Efficiency of NH4 - NO2 conversiton	0.95	nd
	Efficiency of NO2- NO3 conversiton	0.95	nd
	Efficiency of NO3 - N2 conversiton	0	nd
Biofilter processes	Efficiency of COD removal	0.9	nd
Sump (recycle tank)	Total volume	2.125	m^3
Make-up water	Initial volume	2000	m^3
	Dissolved O2 concentration	0	kg/m^3
	Dissolved NO3 concentration	0	kg/m^3

Figure 3

Feed concentration and stocking density in the fishtank

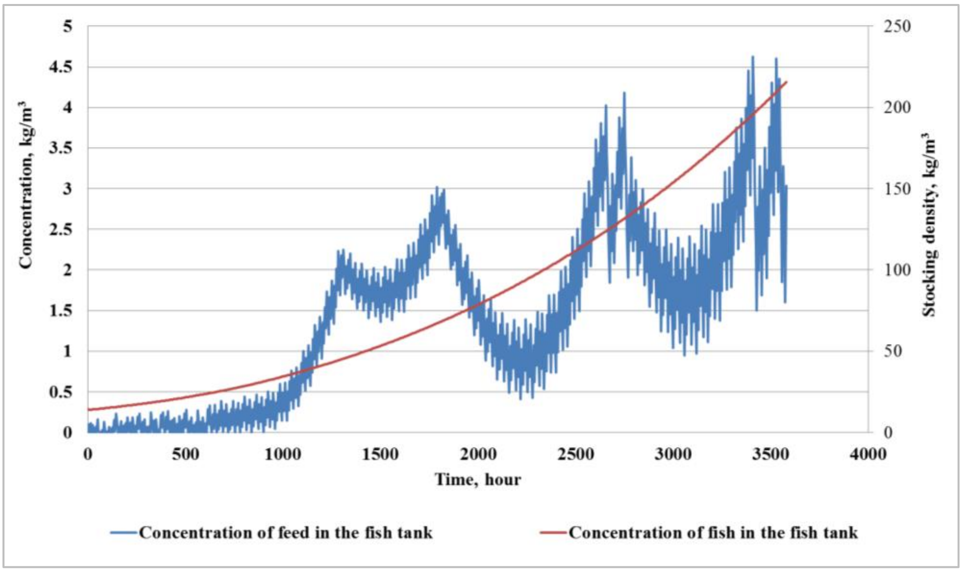


Figure 4

Average weight of fishes during 150 days

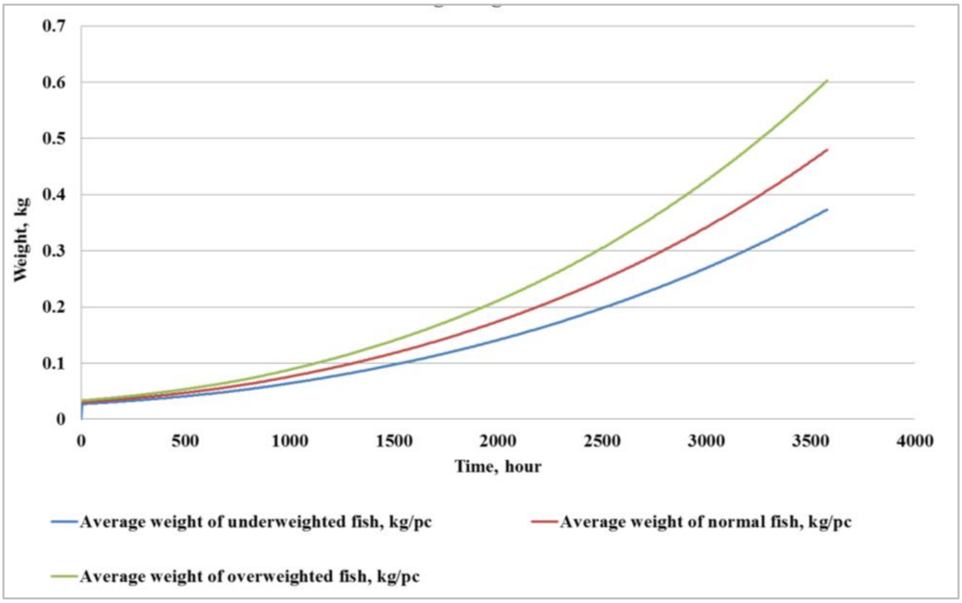


Figure 5

Dissolved components in the fishtank

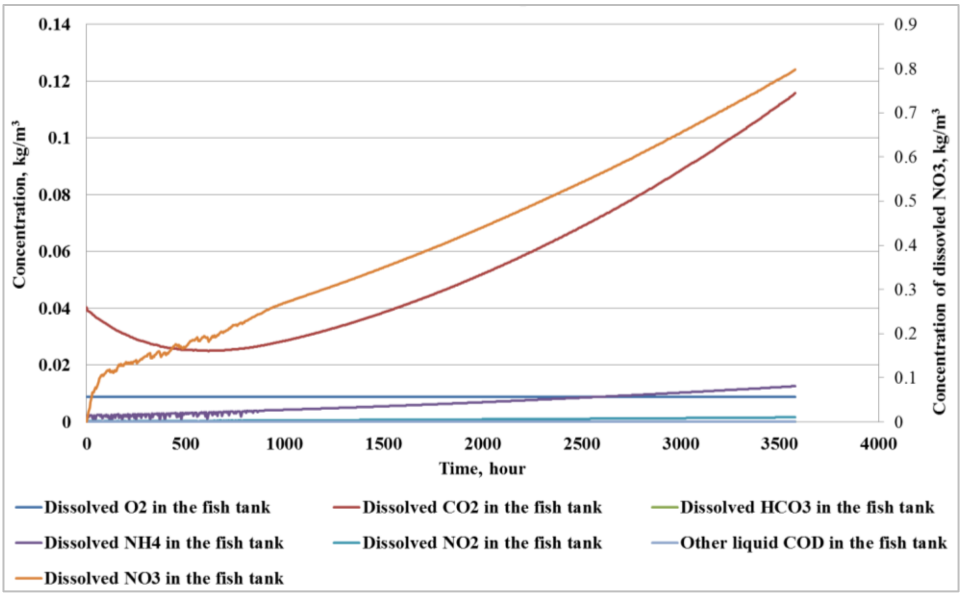


Table 2

Sensitivity of specific pollution taxes and water costs to actually changed recirculation technology parameters

Code of scenario	0 (Ref.)	1	2	3	4	5	6	7	8
Water exchange rate in rearing tank (1/day)	5	5	5	5	4	4	6	4	6
Recirculation rate	0.95	0.95	0.95	0.9	0.9	0.95	0.95	0.9	0.9
Efficiency of biofilter	0.95	0.6	0.3	0.6	0.6	0.95	0.95	0.95	0.95
Specific pollution taxes (HUF/kg net production)[1]	12.1	12.8	14.0	13.3	13.3	12.1	12.2	12.3	12.3
Specific water withdrawal (m^3/kg net production)	0.66	0.66	0.66	1.32	1.05	0.53	0.79	1.05	1.57
Specific water cost (HUF/kg net production)[2]	28.1	28.1	28.1	55.9	44.4	22.4	33.4	44.4	66.5

[1] *Emission costs are calculated based on simulated quantity of discharged COD, NH_4, NO_3 and NO_2 and discharge fee tables contained by the Act LXXXIX. of 2013 on Environmental pollution taxes*

[2] *Costs of water are calculated from BMOKF (2016). For the calculation we assumed that the category of supply water was classified as secondary quality aquiferic water.*

CONCLUSIONS

The presented preliminary work has demonstrated that the applied modelling methodology, based on the Direct Computer Mapping of programmable structures, makes the simulation based detailed analysis of the complex Recirculating Aquaculture Systems possible.

The analysis of the first results have underlined that the complexity and dynamics of the investigated process system really need the utilization of the sophisticated dynamic model based decision support for appropriate design and control.

The model based analysis can essentially contribute to the final configuration of the pilot system and to the preparation and evaluation of pilot tests.

Limited by the available data and experimental knowledge, in this work we focused on the effects of the recirculation and water exchange rates, chosen by the farm management, as well as of the biofilter efficiency. The results underline that the cost of water supply and pollution taxes represent a considerable part of costs.

The experiences highlight that the economic evaluation of planning and control alternatives for these complex systems is almost impossible without the detailed, dynamic simulation of the underlying processes.

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