Modelling, Control, and Optimization of a Recirculating Aquaculture System

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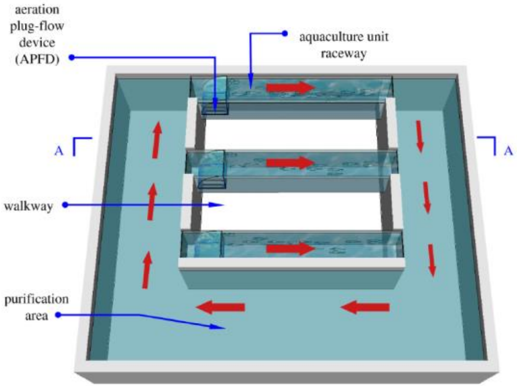
Agenda

Aquaculture Background

The Food and Agriculture Organization of the United Nations (FAO) recognizes the capacity of aquaculture for further growth and demands for more sustainable strategies.

Main categories:

- Land-based vs offshore farming
- Extensive vs intensive farming
- According to water circulation



Aquaculture Background

Land-based farming

Land-based farms are fish farms built in the ground, for example as ponds, or on the ground, as tanks in industrial facilities.

Challenges:

- Maintain environment conditions;
- Avoid spread of diseases due to usually high stock density (number of fish per volume unit);
- Potentially larger investment

Offshore farming

Offshore farms are fish farms located in the sea as, for example, net cages.

Challenges:

- Adapt to changes in the environment conditions;
- Avoid escaping of fish;
- Avoid contact with pathogenic bacteria from outside or inside of the process;
- Avoid spread of diseases due to usually high stock density (number of fish per volume unit);

Aquaculture Background

Extensive farming

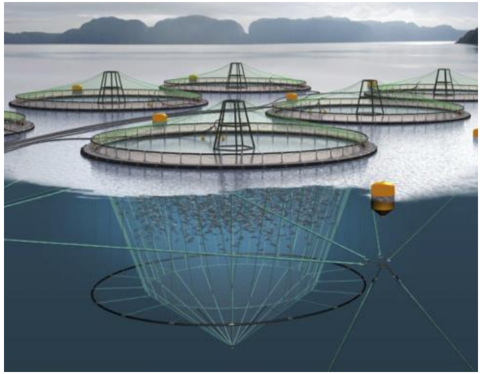
- Extensive farming are fish farms that cultivate or have the source of fish food available.

Intensive farming

- Intensive farming are fish farms that rely completely on external food source.

"Manual feeding control is a talent" but it is extremely **not** recommended!

Aquaculture Background



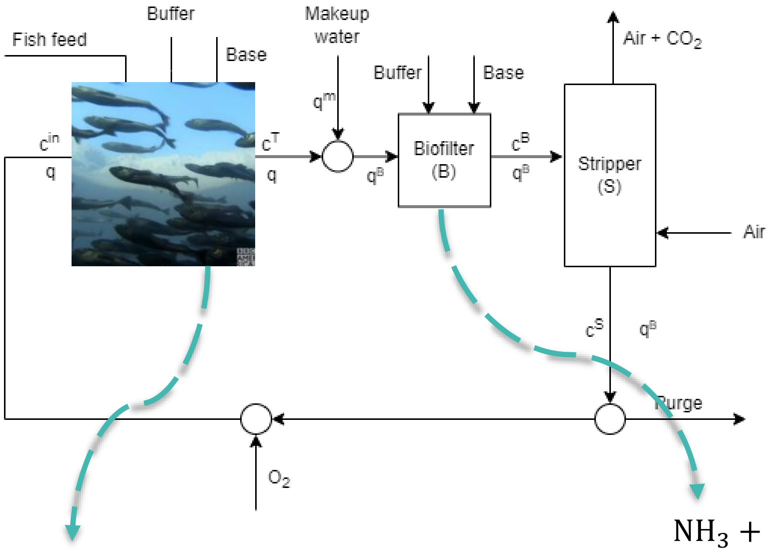
Motivation

Fish farms are being operated partially manually.

Advanced control structures can drive the system to near optimal conditions, generating higher growth rate, with less human intervention.

Models that incorporate the fish metabolism with the water quality model are too complex for optimization and control purposes and are prone to have numerical issues.

RAS Process Description



$$H_2CO_3 \overset{K_1}{\longleftrightarrow} H^+ + HCO_3^-$$

$$HCO_3^- \overset{K_2}{\longleftrightarrow} H^+ + CO_3^{2-}$$

$$NH_4^+ \overset{K_3}{\longleftrightarrow} H^+ + NH_3$$

$$H_2O \overset{K_w}{\longleftrightarrow} H^+ + OH^-$$

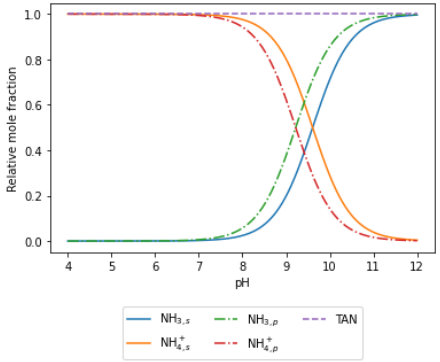
$$NH_3 + 2O_2 \longrightarrow NO_3^- + H^+ + 2H_2O$$

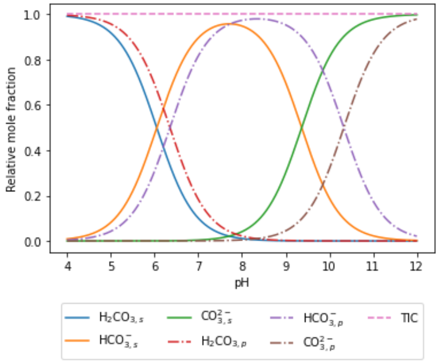
$$1 \text{ kg feed} + 0.45 \text{ kg } O_2 \longrightarrow 0.9 \text{ kg fish biomass} + 0.48 \text{ kg } CO_2 + 0.047 \text{ kg } NH_3 + \text{waste}$$

RAS Models

There has been mainly two models of RAS[1][2], and they do not consider the effect of pH.

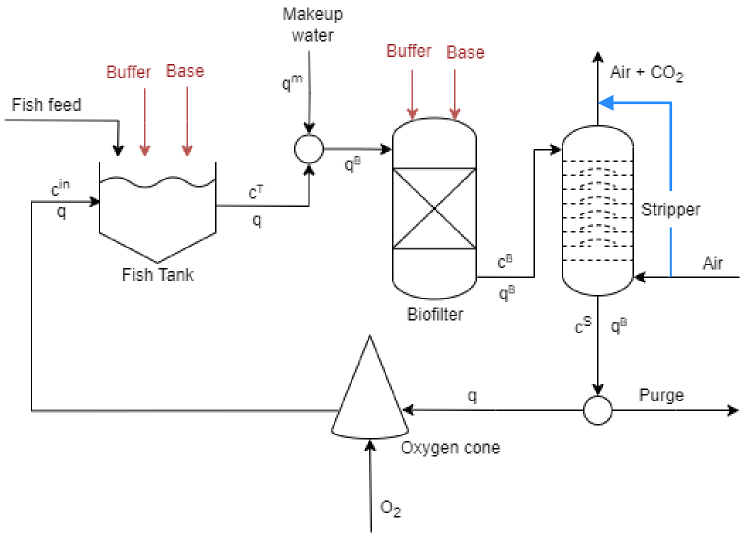
- The models included how the fish growth can affect the water quality, but they did not include pH, which is one of the main variables to be monitored.
- The pH, salinity and temperature affect the ammonia-ammonium equilibrium, and the carbonate system.





[1] Wik *et al*. 2009; [2] Pedersen *et al*. 2018.

RAS Modelling



States:

$$c^i = \begin{bmatrix} c^i_{alk} \\ c^i_{TIC} \\ c^i_{TAN} \\ c^i_{NO_3^-} \\ c^i_{O_2} \end{bmatrix}$$

$i = in, T, B, S$

Inputs:

Airflow = $\dot{m}_{air}$

Makeup water = q^m

Oxygen flow = $\dot{m}_{O_2}$

Base flow = $\dot{m}^i_{base}$

Buffer flow =$\dot{m}^i_{buffer}$

Recirculation flow = q

$i = T, B$

Disturbance:

Fish feed = F

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RAS Modelling

$$V^T \frac{dc^T}{dt} = q\left(c^{in} - c^T\right) + g^T + h^T$$

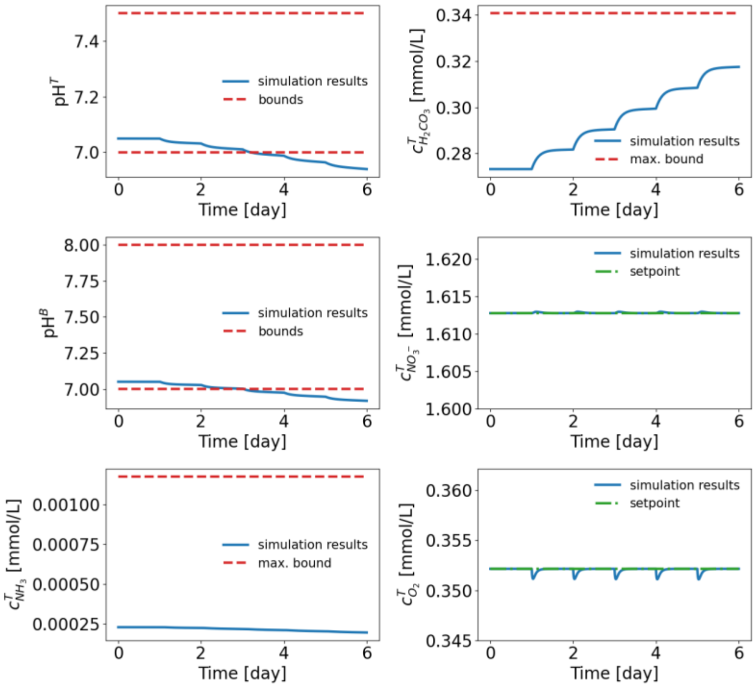
$$V^B \frac{dc^B}{dt} = q^B \left(c^T \frac{q}{q^B} - c^B\right) + g^B + h^B$$

$$g^T = \begin{bmatrix} \dot{m}^T_{buffer} + \dot{m}^T_{base} \\ \dot{m}^T_{buffer} \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad g^B = \begin{bmatrix} \dot{m}^B_{buffer} + \dot{m}^B_{base} \\ \dot{m}^B_{buffer} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$h^T = \begin{bmatrix} \lambda_{NH_3} F \\ \lambda_{CO_2} F \\ \lambda_{NH_3} F \\ 0 \\ -\lambda_{O_2} F \end{bmatrix} \quad h^B = \begin{bmatrix} -2q\xi^B c^T_{TAN} \\ 0 \\ -q\xi^B c^T_{TAN} \\ q\xi^B c^T_{TAN} \\ -2q\xi^B c^T_{TAN} \end{bmatrix}$$

$$c^i_{alk} = c^i_{TIC} \frac{K_1 c^i_{H^+} + 2K_1K_2}{\left(c^i_{H^+}\right)^2 + K_1 c^i_{H^+} + K_1K_2} + \frac{K_w}{c^i_{H^+}} - c^i_{H^+} + c^i_{TAN} \frac{K_3}{c^i_{H^+} + K_3} \qquad i = T, B, S$$

Dynamic Simulation – F step change



Model Validation

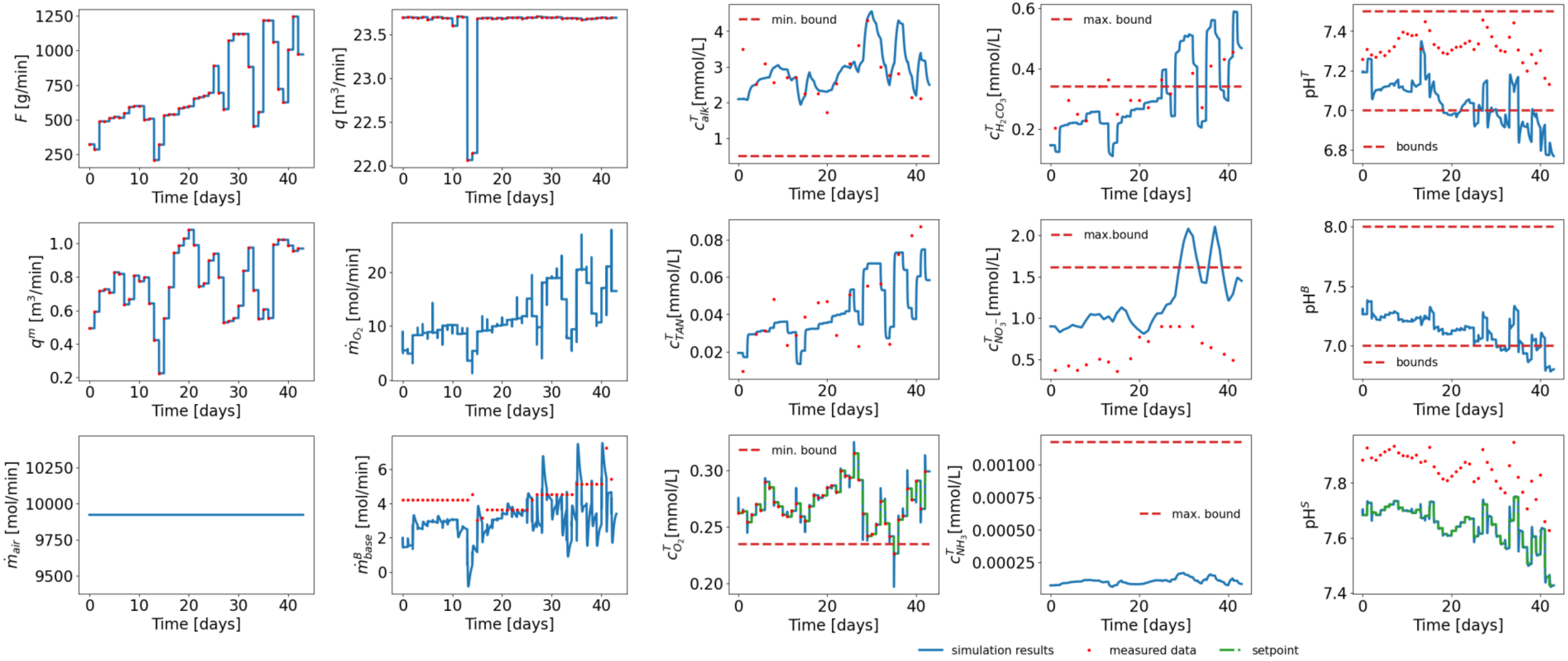
Measured variables from real data:

- Flow rate of makeup water, q^m.
- Recirculation rate, q.
- Oxygen saturation in the fish tank.
- Daily average of pH after the stripper.
- Base flow rate added to the biofilter.

Lab data:

- $\mathrm{H_2CO_3}$, $\mathrm{NO_3^-}$, alkalinity, and TAN concentrations.
- Fish feed, F, was measured daily as cumulated mass of food.

Model Validation



Process Constraints

Chemical components that are toxic to the fish when in higher concentration:

- Ammonia (NH_3)
- Nitrate (NO_3^-)
- Carbon dioxide (CO_2)

The fish also demand a minimum concentration of oxygen, and the pH in the tank should be between 7 and 7.5 for maximum growth rate.

The bacteria in the biofilter are more productive if the pH is between 7 and 8.

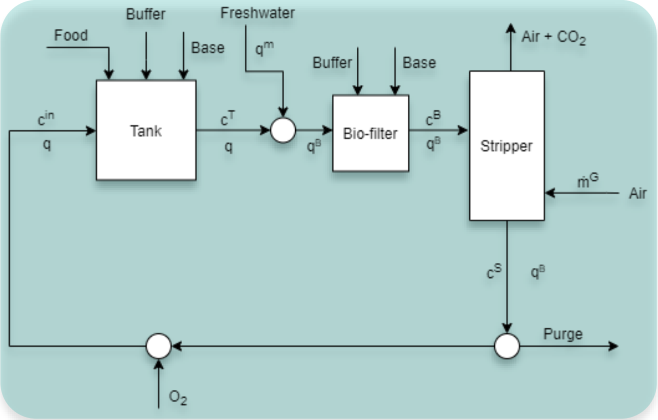
Optimization Problem

Degrees of freedom:

- Makeup water
- Inflow to tank
- Oxygen inlet
- Air inlet
- Base/buffer addition in the tank/biofilter

Disturbance:

- Fish food (measured)

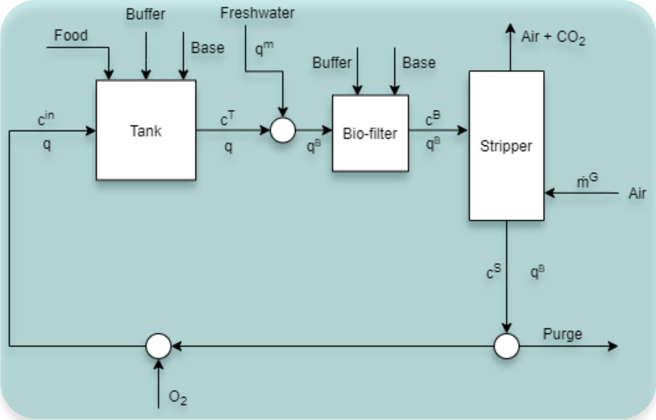


Optimization Problem

$$\min_{x,z,u} \; J(x,z,u)$$

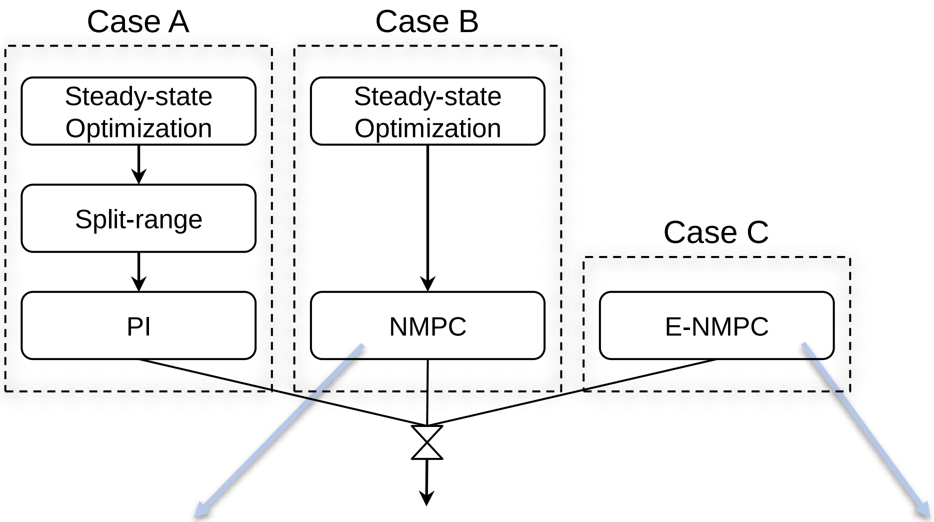
s.t.

$$\dot{x} = f_d(x,z,u)$$
$$f_a(x,z,u) = 0$$
$$g(x,z,u) \leq 0$$
$$x(0) = x_0$$



$$J = S(u_k) = p_1(1-r)q^B + p_2\dot{m}_{air} + p_3 \sum_{i=T,B} \dot{m}^i_{base} + p_4 \sum_{i=T,B} \dot{m}^i_{buffer} + p_5 q^m + p_6 q$$

Control Structures



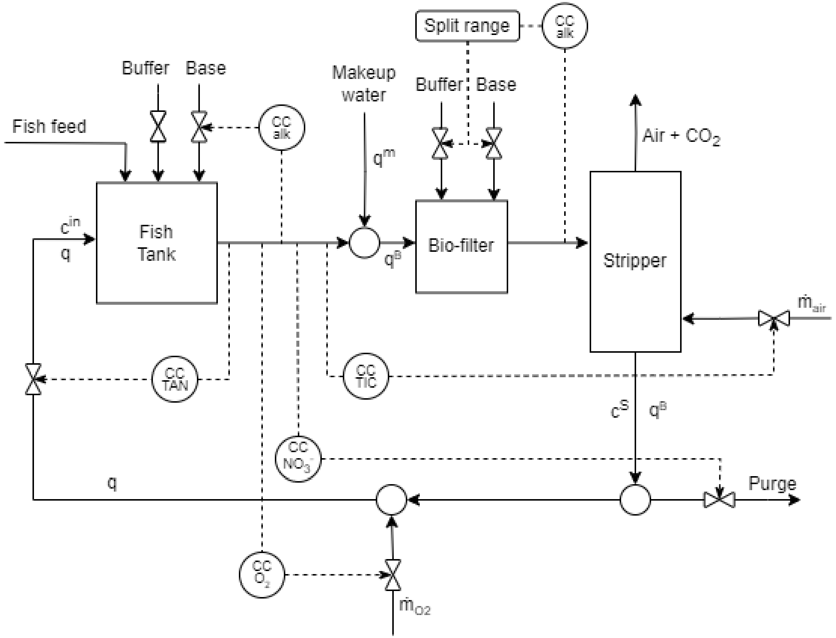
NMPC cost function:

$$J = \sum_{k=0}^{N-1} \left[\| x_k - x_{opt} \|_Q^2 + \| u_k - u_{k-1} \|_R^2 \right]$$

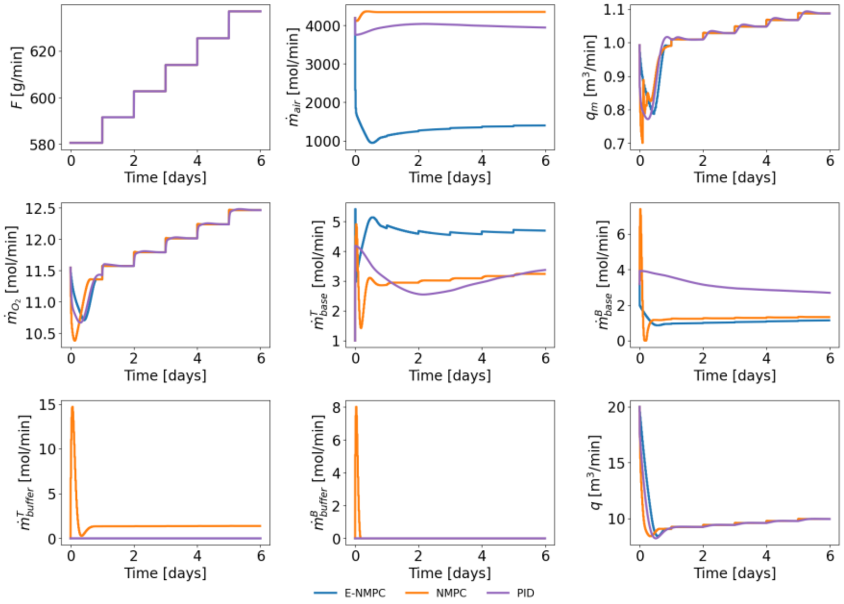
E-NMPC cost function:

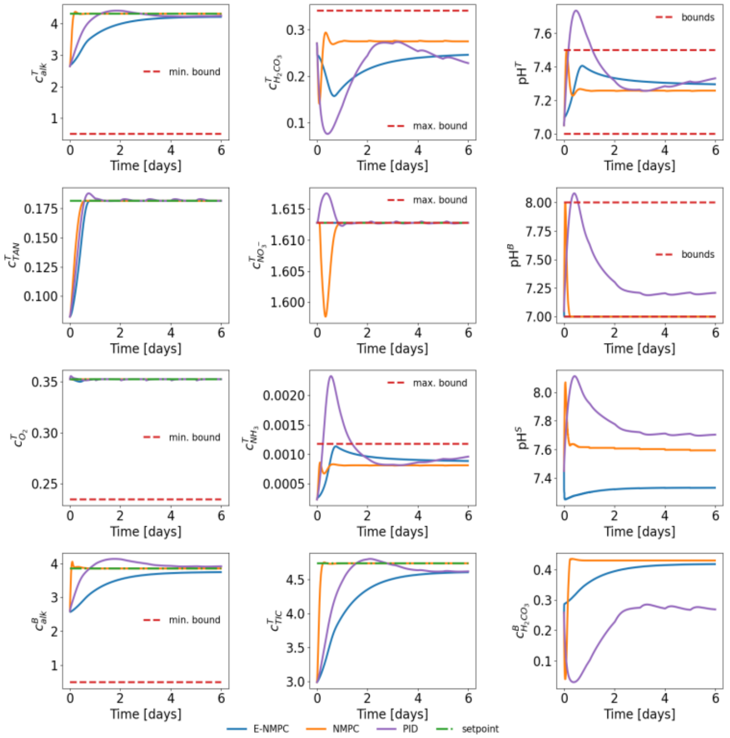
$$J = \sum_{k=0}^{N-1} \left[S(u_k) + \| u_k - u_{k-1} \|_R^2 \right]$$

PI Structure



Advanced Control Performances





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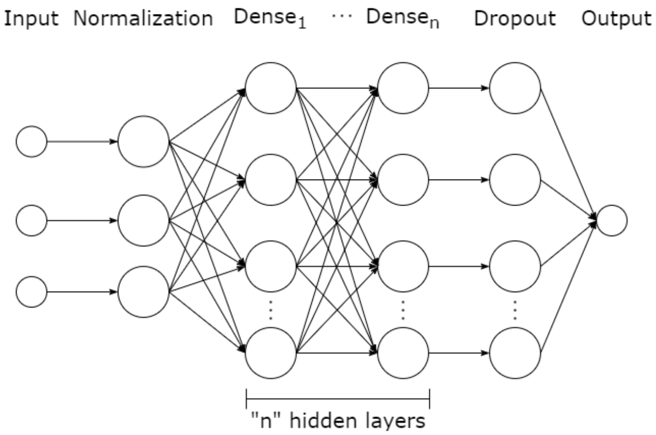
Monitoring Water Quality

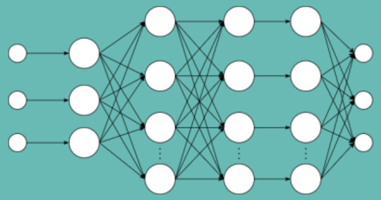
Some key variables are hard or too expensive to measure, so it is important to develop alternative monitoring methods.

Auto-keras is an automatic neural architecture search tool in Python.

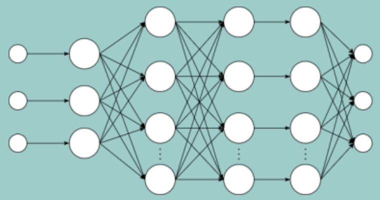


Monitoring Water Quality

MIMO-MLP

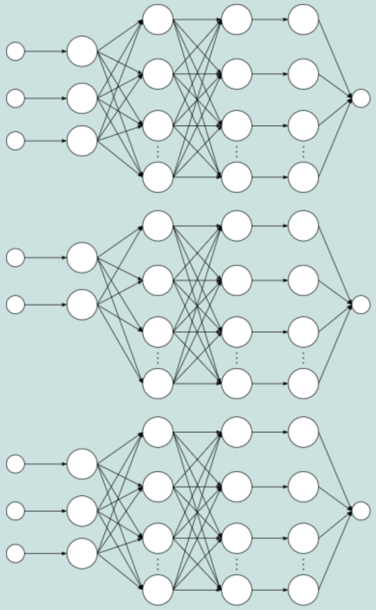


Hybrid model



$$c^T_{NH_3} = \frac{K_3(S,T)\, c^T_{NH_4^+}}{c^T_{H^+}}$$

MISO-MLP



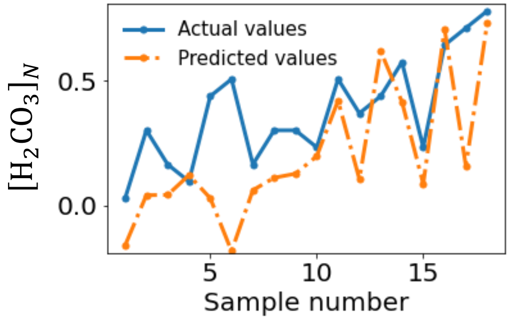
Monitoring Water Quality

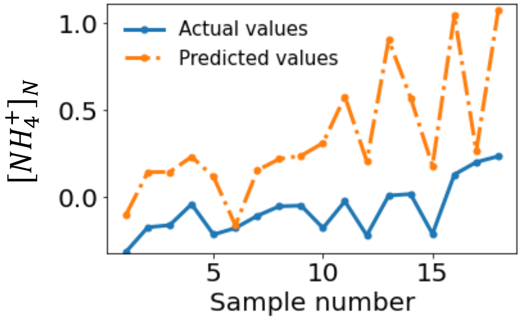
RMSE index comparison

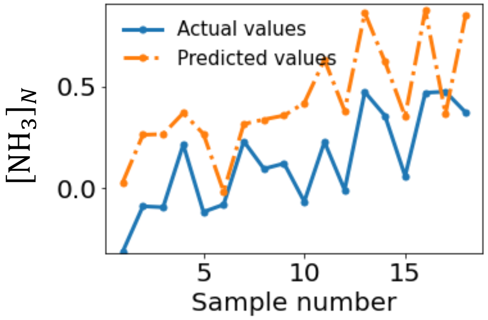
Output	MISO-MLPs	Hybrid	MIMO-MLP
$c^T_{H_2CO_3}$	0.0645	0.0787	0.0694
$c^T_{NH_4^+}$	0.1204	0.1201	0.1230
$c^T_{NH_3}$	0.1322	0.2611	0.1351
Final	0.1097	0.1720	0.1129

Monitoring Water Quality

Testing the MISO-MLP models with real data.







The trend of the predicted values turned out to be the same, meaning that the models could not capture the particularities of each variable.

Final Remarks

- The developed model proposes a way to simplify the modelling of RAS after many attempts of previous studies in literature to integrate the RAS subsystems with the fish metabolism.
- The proposed model was validated with real data.

It showed excellent numerical performance, and suitability to its purposes.

Final Remarks

- PI controllers gave slower response due to use of strong base and pH spike limitations.
- NMPC drove the system to the steady-state condition with a better trajectory and the pH was kept within the bounds, as designed.
- E-NMPC provided a smother trajectory than the NMPC, but it stabilizes at different values (non-optimal steady state).
- Taking away 4 degrees of freedom, would just leave one decision, where to add the pH adjustment, simplifying the process control a lot, but generating sub-optimal solutions.

The control structures proved to be essential to the operability of the system and drove the system to a more financially beneficial operating condition.

Final Remarks

- The RAS process has some key variables that are hard to measure in real time, such as CO_2 and ammonia.
- To complement the lab measurements, which are not frequently done, alternative methods for monitoring were tested.
- The automatic neural architecture search tool used in this work did not provide a good surrogate model.

Other types of surrogate models should be tested for this application.

Thank you for your attention!

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