Economic model predictive control of a recirculating aquaculture system

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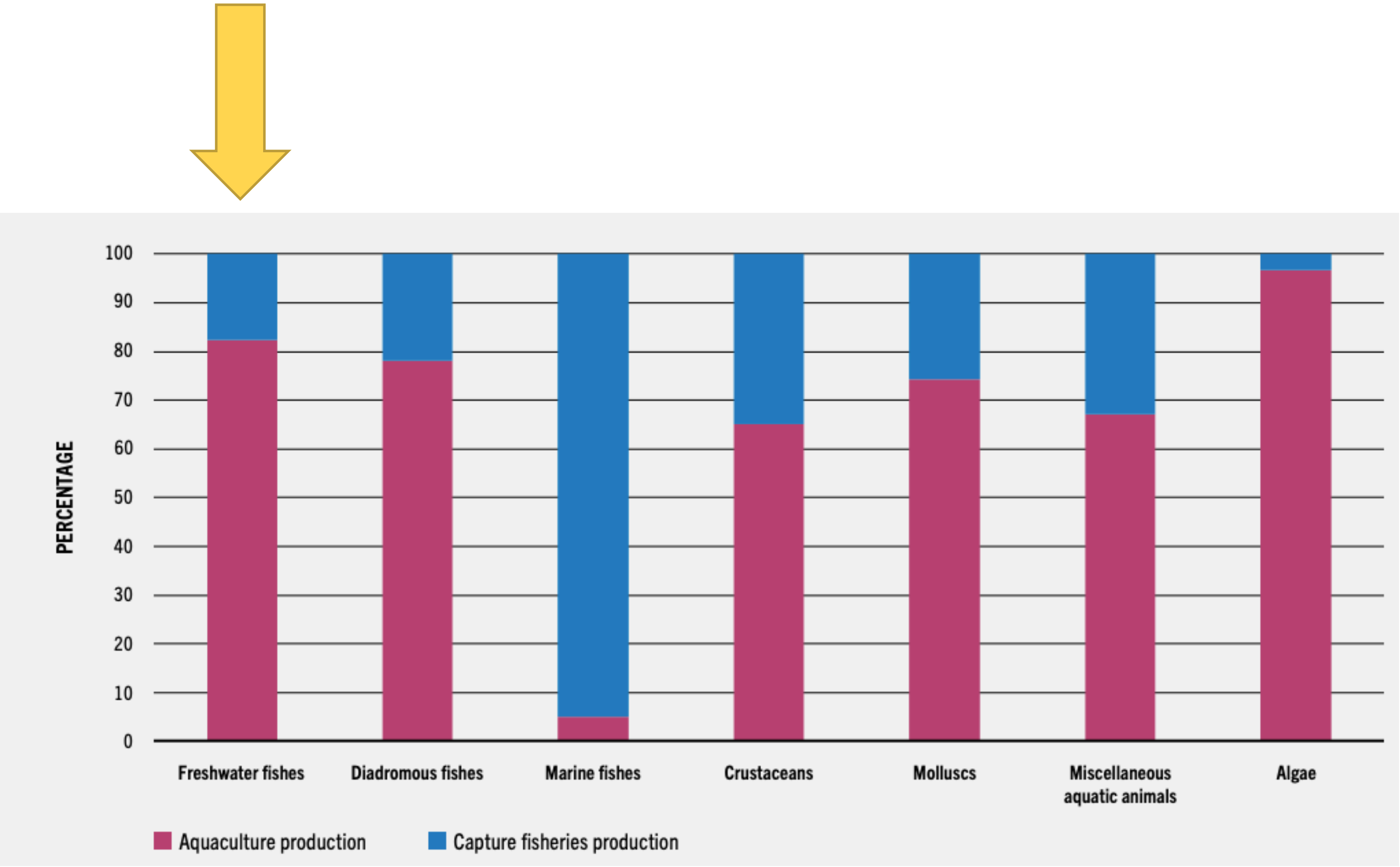
Outline

1. RAS introduction
2. Gaps and objectives
3. Formulation
4. Results
5. Conclusions and future work

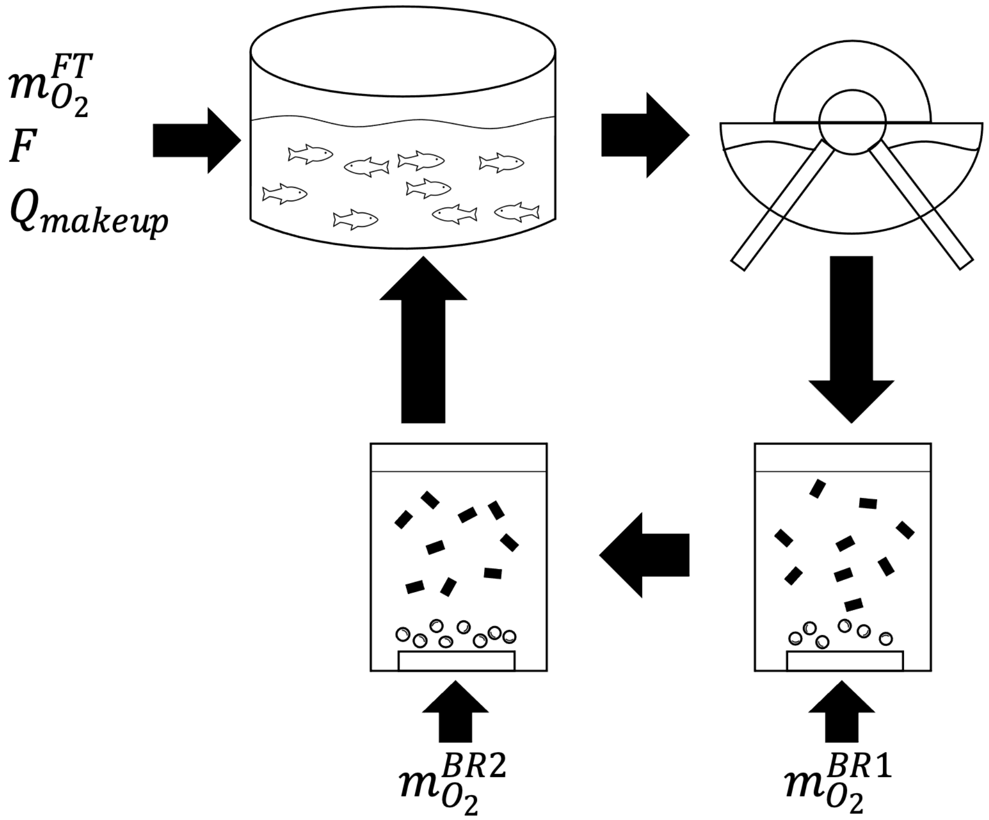
Aquaculture

- Human-reared growth and cultivation of aquatic organisms
- Comprises 123/214 million tn of total annual seafood production (FAO, 2022)
- Benefits:
  - Meets increasing seafood demand
- Drawbacks:
  - Water usage
  - Waste treatment



Recirculating aquaculture system (RAS)

- Benefits:
  - Reduces feed water use
  - Treats/separates waste
- Still nascent owing to:
  - Energy consumption
  - High cost



Control approaches in RAS

- Classical control (PID, fuzzy control)
  - pH control (Summerfelt et al., 2015)
  - Water temperature (Farghally et al., 2014)
- MPC and MHE (Kamali et al., 2022, 2023)
  - Nonlinear mechanistic MPC
  - MHE to remove state accessibility assumption (30/73 states)
- Economic MPC (Dos Santos et al., 2022)
  - Used simplified process model
  - Only considered operational (i.e., utility) <u>costs</u>

*No economically optimal operational scheme that considers fish growth and utilities jointly.

Motivation and objectives

Motivation

- Previous economically optimal operational schemes make simplifications
- Economical operation of RAS can promote its further uptake

Objectives

- Deploy a RAS that jointly considers fish profits and utility usage
- Use time-varying controls on RAS
- Determine the optimal “batch” length for RAS

Economic MPC (EMPC)

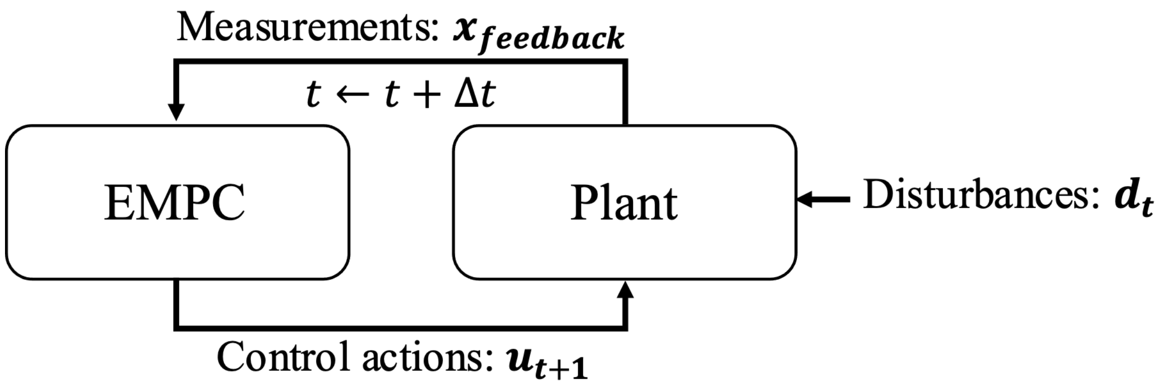
$$\max_{\boldsymbol{u}_{t+i}\forall i\in\{1,\dots,C\}} \boxed{\phi(\boldsymbol{x}_{t+i},\boldsymbol{u}_{t+i})} - \sum_{i=0}^{C} \|\Delta \boldsymbol{u}_{t+i}\|_{\boldsymbol{K}}^2$$

$$\boxed{\boldsymbol{f}(\boldsymbol{x}_{t+i},\boldsymbol{u}_{t+i})} = \boldsymbol{x}_{t+i+1} \qquad \forall i \in \{0,\dots,C-1\}$$

$$\boldsymbol{x}_t = \boldsymbol{x}_{feedback}$$

$$\boldsymbol{g}(\boldsymbol{x}_{t+i},\boldsymbol{u}_{t+i}) \le \boldsymbol{0} \qquad \forall i \in \{0,\dots,C\}$$

$$\boldsymbol{u}_l \le \boldsymbol{u}_{t+i} \le \boldsymbol{u}_u \qquad \forall i \in \{0,\dots,C\}$$



In the RAS case, what do $\boldsymbol{f}$ and ϕ look like?

RAS model (f) and implementation

- Model (f) comprised of 73 states
- Sampled every 0.1 days with a 5-day horizon ($C = 50$)
- Manipulated variables:
  - Oxygen to FT ($m_{O_2}^{FT}$)
  - Feed rate (F_{fish})
  - Water makeup (Q_{makeup})
  - Air to BRs ($m_{O_2}^{BR1}, m_{O_2}^{BR2}$)

Phenomenon	Equations (Kamali et al., 2022)
Fish (trout) growth	$\frac{dW}{dt} = bR - abF_{fish} - KW^n$
Population growth	$\frac{dN}{dt} = -M_{ins}N$
Waste buildup	$V_{FT}\frac{dZ_i}{dt} = Q_{FT}(Z_{i,in} - Z_i) + \omega_i - L_i$
Aeration and oxygen addition	$V_j\frac{dS_{O_2}^j}{dt} = Q_j\left(S_{O_2,in}^j - S_{O_2}^j\right) - r_{O_2}^j + m_{O_2}^j$
Biological reactors	$V_j\frac{dS_i^j}{dt} = Q_j(S_{i,in}^j - S_i^j) + V_j r_i^j$

RAS economics (ϕ)

Divide economics into profits (π) and costs (χ):

$$\phi = \phi_\pi - \phi_\chi$$

Fish are the product of RAS; their final mass (W) and population (N) are harvested:

$$\phi_\pi = P_{fish} W_{t+C} N_{t+C}$$

The costs incurred are oxygen ($\dot{m}_{O_2}$), feed (F), energy (D) expended (i.e., integrated) in a RAS batch:

$$\phi_\chi = \Delta t \sum_{i=0}^{C} \left(P_{O_2} \dot{m}_{O_2,t+i} + P_f F_{t+i} + P_e D_{t+i} \right)$$

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RAS batch length

EMPC for RAS is operated in a receding horizon manner to deal with disturbances: batch length is not considered as an explicit decision variable.

- Batch length is determined by tracking the profit over the time elapsed (T):

$$R = \phi_{\pi}(T) - \int_0^T \phi_{\chi}(t)\, dt$$

- such that

$$t_{batch} = \arg\max_t R(t)$$

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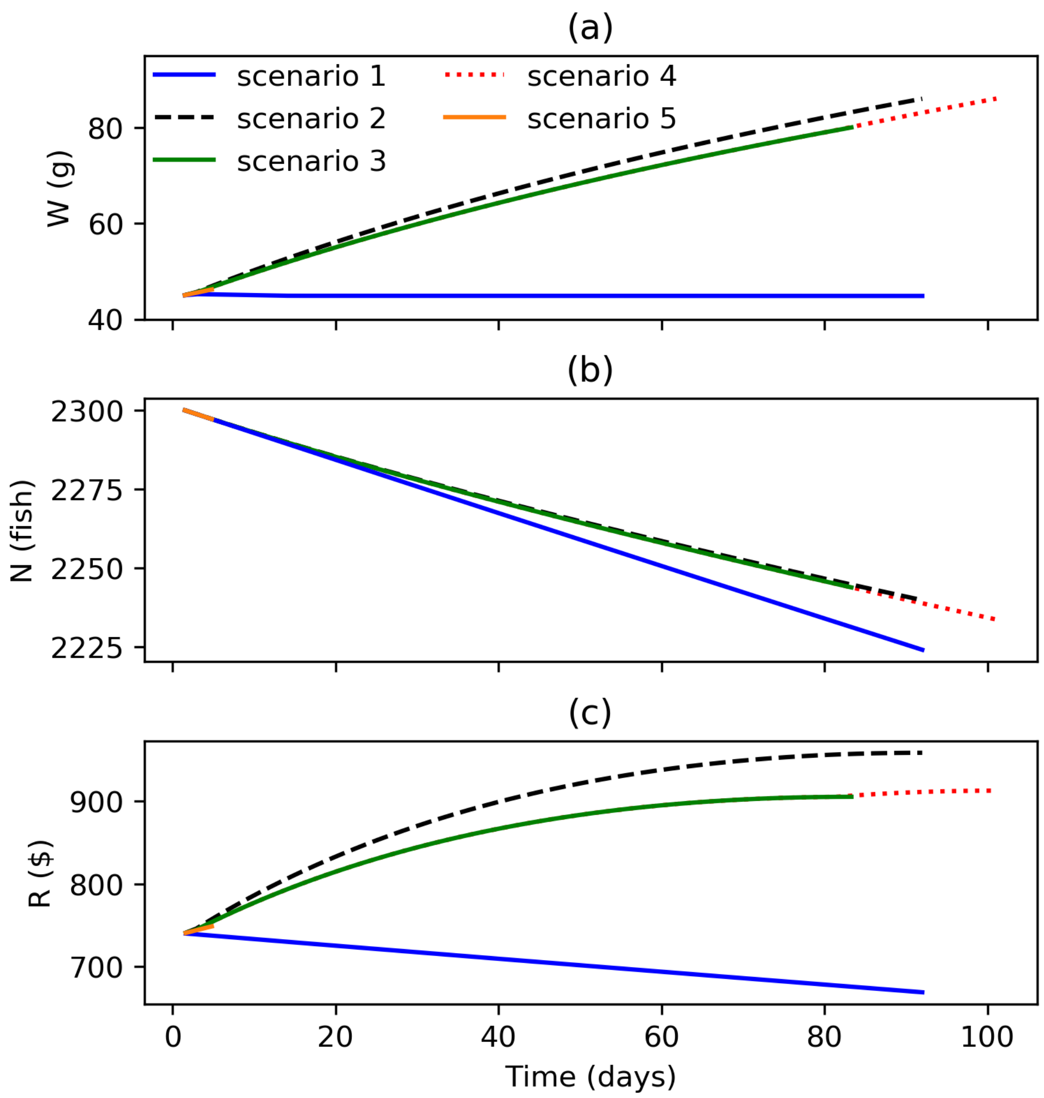
Overall results

- Different temperature scenarios considered for RAS operation.
- Significant variability in profit and batch length observed as a function of temperature.
- 10°C found to be too cold for fish growth
- Compared to starting value of fish ($740.18) all other EMPC-operated scenarios experience significant increase in fish profits.
- Constant set point scenario (Kamali et al., 2022) observed to result in little valorisation

Scenario	Temperature	t_{batch} (days)	R ($)
1	10°C	0	740.18
2	15°C	92.1	958.61
3	20°C	83.4	905.41
4	20 → 15°C	101.2	912.83
5	20°C (u_{nom})	4.9	748.98

Key operational metrics

- Fish weight shown to increase in all except for low-temperature case (scenario 1)
- Fish population decreases over time due to natural mortality; scenario 1 has increased mortality
- Trend of stagnating profit can be observed as final batch time reached



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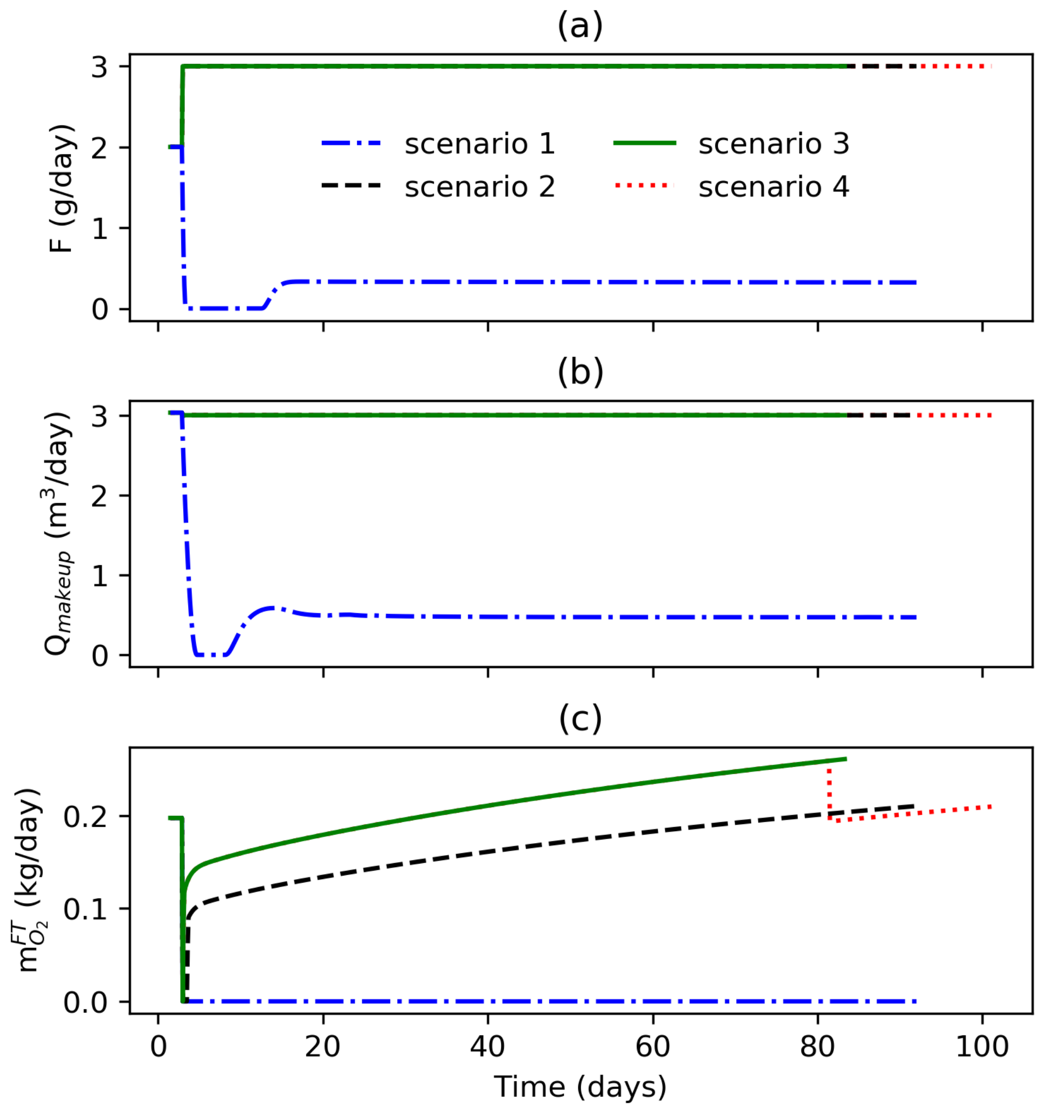
Manipulated variables

- Feed and water makeup at upper bound to maximize growth except in low temperature scenario 1
- Low temperature scenario 1 settles at non-zero feed and makeup conditions to balance mortality and utility use
- Increasing oxygen feed with time to meet the oxygen needs of growing fish



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Conclusions

- The EMPC was able to significantly increase fish profit through:
  - Weight increase
  - Low mortality rates
  - Minimal utility usage
- Fish weights too small for wholesale (D'Agaro et al., 2022); grading required

Future works

- Uncertainty
- Energy balance
- Simultaneous design and control

Thank you

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