Comprehensive Analysis of Aerators for Shrimp Farming: Cost Optimization and the Real Cost of “Cheap”

Abstract

Aerator selection is a critical economic decision in shrimp farming, often complicated by the trade-off between initial cost and long-term operational efficiency. This paper presents a comprehensive analysis comparing two aerator options—a cheaper, less efficient model (Aerator 1) versus a more expensive, efficient one (Aerator 2)—within the context of a 1,000-hectare Ecuadorian shrimp farm. Integrating Léon Walras's General Equilibrium Theory and Friedrich von Wieser's concept of Opportunity Cost, the study evaluates the aerators based on technical performance metrics (Standard Oxygen Transfer Rate - SOTR, Adjusted Oxygen Transfer Rate - OTRT, Standard Aeration Efficiency - SAE) derived from calculated Total Oxygen Demand (TOD = 5,443.8 kg O_2/h), and standard financial indicators (Net Present Value - NPV, Internal Rate of Return - IRR, Payback Period, Return on Investment - ROI), alongside a derived profitability coefficient (k). Results demonstrate that despite a higher initial investment ($53,400 difference), the more efficient Aerator 2 yields substantial annual savings ($1.49 million), a significantly positive NPV ($8.21 million), an extremely high IRR (approx. 2,788%), a rapid payback period (approx. 13 days), and a profitability coefficient (k) of 154.81 over a 9-year horizon. Conversely, choosing the cheaper Aerator 1 incurs a significant opportunity cost, equivalent to the present value of forgone savings ($8.27 million). The analysis highlights the economic fallacy of prioritizing low initial costs over efficiency and underscores the importance of applying robust economic principles and accurate technical assessments (rejecting simplistic HP/production rules) for optimizing operational costs and ensuring financial sustainability in shrimp aquaculture.

Keywords: Shrimp Farming, Aquaculture Economics, Aerator Efficiency, Opportunity Cost, Cost Optimization

Introduction: Léon Walras's General Equilibrium Theorem, Opportunity Cost, and its Application to Shrimp Farming

The economic analysis of the optimal choice of aerators in shrimp farming can benefit from the fundamental principles of the General Equilibrium Theorem developed by Léon Walras in the 19th century, complemented by the concept of opportunity cost, introduced by Friedrich von Wieser in 1914. Walras proposed a theoretical framework to understand how interconnected markets reach a simultaneous equilibrium, where supply equals demand in all markets through a system of relative prices (see e.g., equilibrium analysis in aquaculture, Asche et al., 2021; Valderrama et al., 2023). This approach is particularly useful for analyzing complex systems like a shrimp farm, where multiple "markets" (oxygen, energy, shrimp, operating costs) interact and must be balanced to maximize profitability. Meanwhile, opportunity cost, defined by von Wieser in his work Theorie der gesellschaftlichen Wirtschaft (Theory of Social Economics), measures the value of the best alternative forgone when making a decision, providing a key tool to evaluate the implications of choosing between aerator options (Engle, 2010; Jolly & Clonts, 1993; Tveteras, 2009).

Analogy with the Oxygen Market and Opportunity Cost

In shrimp farming, dissolved oxygen is a critical input for shrimp production. We can conceptualize an "internal oxygen market" where **demand** is determined by the biological needs of the shrimp and the microbial activity of the pond, while **supply** depends on the aerators (equipment providing oxygen through their oxygen transfer capacity). Aerators interact with other internal "markets": the energy market (to operate the aerators), the maintenance market (costs associated with their operation), and the replacement market (replacement costs according to their durability). Finally, these markets connect to the external shrimp market, where revenue depends on production and selling price. Walras's Theorem suggests that a general equilibrium is reached when all these markets adjust simultaneously (Asche et al., 2021; Valderrama et al., 2023). For example, an increase in energy cost could reduce the number of aerators the farm can operate, decreasing oxygen supply, which in turn would affect shrimp production and revenue (Boyd & Hanson, 2021; Kumar et al., 2020).

Opportunity cost comes into play when choosing between two types of aerators with different oxygen transfer rates OTR_T and associated costs (Engle, 2010; Jolly & Clonts, 1993; Tveteras, 2009). If we opt for a cheaper but less efficient aerator, the opportunity cost is the net savings that could have been obtained by choosing the more efficient aerator, measured in present value. Mathematically, the opportunity cost CO of choosing Aerator 1 over Aerator 2 is defined as:

$$CO = PV(Savings\ with\ Aerator\ 2) - PV(Savings\ with\ Aerator\ 1)$$

$PV(Savings)$ is the present value of the savings generated by each option, considering operating, maintenance, and replacement costs over the analysis horizon. In this case, since Aerator 1 is less efficient, $PV(Savings\ with\ Aerator\ 1)$ is usually zero (as it represents the less profitable baseline option), therefore:

$$CO = PV(Savings\ with\ Aerator\ 2)$$

This opportunity cost reflects the unrealized utility from prioritizing a lower initial cost over long-term efficiency (Engle, 2010; Tveteras, 2009), a common mistake that can unbalance the shrimp farm's market system.

The Cake Recipe: Why Assuming HP per Pound of Shrimp is Incorrect

A common error in shrimp farm design is assuming a fixed linear relationship between aerator power (measured in HP, horsepower) and shrimp production (in pounds harvested), for example, "X HP per pound of shrimp" (Boyd, 2020; Nunes & Musig, 2013). This simplification is incorrect, and we can understand it through the "cake recipe" analogy. Making a cake requires combining flour, eggs, sugar, and other ingredients in specific proportions; if we double the amount of flour without adjusting the other ingredients, we won't get twice the cake, but an unbalanced product that might not be edible. Similarly, in shrimp farming, production depends on multiple interdependent factors: dissolved oxygen, temperature, salinity, biomass density, water quality, and more. The HP of the aerators does not directly translate into available oxygen; what matters is the OTR_T, which varies between aerators even if they have the same power (Boyd, 2015; Kumar et al., 2020).

Assuming a fixed HP-per-pound ratio ignores these interdependencies and can lead to inefficient decisions, such as overinvesting in aerators with low OTR_T, which increases operating costs without proportionally improving production (Boyd & Hanson, 2021; The Fish Site, 2021). Furthermore, this decision has a significant opportunity cost: the savings that could have been obtained by choosing a more efficient aerator are lost, affecting long-term profitability (Engle, 2010; Tveteras, 2009). Our analysis seeks a general equilibrium that considers the actual oxygen demand, the costs associated with the aerators, the revenue generated by shrimp production, and the opportunity cost of the decisions made.

Original Equation of Léon Walras's General Equilibrium

Walras formalized general equilibrium in a system of $n + k$ markets (where n are consumer goods and k are factors of production). In his model, each market has a supply and demand equation, and prices adjust until all markets are simultaneously in equilibrium. Mathematically, the system is represented as follows:

Let $p_1, p_2, ..., p_n$ be the prices of the n consumer goods, and $w_1, w_2, ..., w_k$ be the prices of the k factors of production. The equilibrium equations are:

- **Demand and supply of consumer goods**: For each good $i = 1, 2, ..., n$:

$$D_i\left(p_1, p_2, ..., p_n, w_1, w_2, ..., w_k\right) = S_i\left(p_1, p_2, ..., p_n, w_1, w_2, ..., w_k\right)$$

- **Demand and supply of factors of production**: For each factor $j = 1, 2, ..., k$:

$$D_j\left(p_1, p_2, \ldots, p_n, w_1, w_2, \ldots, w_k\right) = S_j\left(p_1, p_2, \ldots, p_n, w_1, w_2, \ldots, w_k\right)$$

- **Walras's Condition (Walras's Law)**: The sum of the value of excess demands (or supplies) across all markets must be zero:

$$\sum_{i=1}^{n} p_i\left(D_i - S_i\right) + \sum_{j=1}^{k} w_j\left(D_j - S_j\right) = 0$$

Walras proposed a price adjustment mechanism (the "tâtonnement") to find the equilibrium prices $\left(p_1^*, p_2^*, \ldots, p_n^*, w_1^*, w_2^*, \ldots, w_k^*\right)$. In shrimp farming, the "prices" are the implicit costs of resources, and equilibrium is reached when the choice of aerator optimizes total costs while satisfying oxygen demand and maximizing net profits, considering the opportunity cost of the alternatives not chosen (Engle, 2010; Jolly & Clonts, 1993; Valderrama et al., 2023).

Standard Equations for Aerator Evaluation and Financial Analysis

Before addressing the specific case, it is essential to establish the standard equations used to evaluate aerator performance and conduct financial analysis. These metrics are widely accepted in the industry and provide a basis for comparing investment options.

Standard Oxygen Transfer Rate (SOTR)

The **SOTR** (Standard Oxygen Transfer Rate) measures the amount of oxygen an aerator can transfer to water per hour under standard conditions: temperature of 20°C, salinity of 0 ppt, standard atmospheric pressure (1 atm), and initial dissolved oxygen of 0 mg/L (Kumar et al., 2020; Sadek et al., 2020). It is expressed in kg O_2/h per aerator and is provided by the manufacturer as a technical specification.

The SOTR is calculated from the oxygen mass transfer coefficient K_La, which describes the rate at which oxygen transfers from air to water. This coefficient depends on temperature and salinity and is adjusted to 20°C and 0 ppt (K_La_{20}) for standard conditions. The general formula for oxygen transfer in an aeration system is:

$$\frac{dC}{dt} = K_La_T \times (Cs - C)$$

Where:

- C: dissolved oxygen concentration in water (mg/L) at time t.
- Cs: oxygen saturation concentration (mg/L) at temperature T and salinity of the experiment.
- K_La_T: mass transfer coefficient at temperature T (h^{-1}).

Integrating this differential equation with the initial condition $C = 0$ at $t = 0$:

$$ln\left(\frac{Cs-C}{Cs}\right) = -K_La_T \times t$$

Or, equivalently:

$$C = Cs \times \left(1 - e^{-K_La_T \times t}\right)$$

Obtaining K_La_T Using t_{10} and t_{70}

To determine K_La_T experimentally, an aeration test is performed in a test tank under experimental conditions. In this case, a salinity of $25\,ppt$ is selected, which minimizes osmotic transfer in shrimp (like *Penaeus vannamei*), as it is close to isotonic salinity, reducing osmotic stress and optimizing test conditions. The temperature is maintained at $25°C$ to reflect typical shrimp farm conditions. Starting with deoxygenated water ($C = 0\,mg/L$), the time taken for dissolved oxygen to reach certain saturation percentages is measured. Commonly, times t_{10} and t_{70} are used, corresponding to the time needed to reach 10% and 70% saturation, respectively:

- At $t = t_{10}$, $C = 0.1 \times Cs$:

$$K_La_T \times t_{10} = -\ ln(0.9) \approx 0.10536$$

- At $t = t_{70}$, $C = 0.7 \times Cs$:

$$K_La_T \times t_{70} = -\ ln(0.3) \approx 1.2040$$

In practice, K_La_T is calculated directly using the difference between t_{70} and t_{10} to reduce experimental errors:

$$K_La_T = \frac{ln(3)}{t_{70}-t_{10}} \approx \frac{1.0986}{t_{70}-t_{10}}$$

Adjustment to Standard Conditions (K_La_{20})

The experimentally obtained K_La_T must be adjusted to standard conditions $(20°C\ and\ 0\ ppt)$ to calculate the SOTR.

Temperature Adjustment

The relationship between K_La_T and K_La_{20} is modeled with a temperature correction factor θ (typically $\theta = 1.024$ for clean water) (Sadek et al., 2020):

$$K_La_T = K_La_{20} \times \theta^{(T-20)}$$

Isolating K_La_{20}:

$$K_La_{20} = \frac{K_La_T}{\theta^{(T-20)}}$$

Salinity Adjustment

Salinity affects K_La because it influences oxygen solubility and mass transfer dynamics. For SOTR, K_La at $0\,ppt$ is required. The effect of salinity is corrected using an adjustment factor β (Sadek et al., 2020). According to the literature, K_La slightly decreases with increasing salinity. A common empirical relationship is:

$$\beta = 1 - 0.0002 \times S$$

Where S is the salinity in ppt. The relationship between K_La at different salinities is:

$$K_La_S = K_La_{S=0} \times \beta$$

Therefore, to adjust K_La_{20} (calculated at salinity S) to $0\,ppt$:

$$K_La_{20,S=0} = \frac{K_La_{20,S}}{\beta}$$

The salinity adjustment increases K_La_{20} as salinity decreases, reflecting that at lower salinity ($0\,ppt$) oxygen transfer is slightly more efficient (Sadek et al., 2020).

SOTR Calculation

With K_La_{20} adjusted to $0\,ppt$, the SOTR is calculated as:

$$SOTR = K_La_{20,S=0} \times Cs_{100\%}(0, ppt, 20°C) \times V \times 10^{-3}$$

Where:

- $K_La_{20,S=0}$: mass transfer coefficient at $20°C$ and $0\,ppt$ (h^{-1}).
- $Cs_{100\%}(0, ppt, 20°C)$: Oxygen saturation concentration at $20°C$ and $0\,ppt$ (generally $\approx 9.0\,mg/L$).
- V: test tank volume (L).

- 10^{-3}: conversion factor from mg to kg.

In practice, the SOTR is provided by the manufacturer (Kumar et al., 2020), but its experimental calculation, including adjustments for temperature and salinity (Sadek et al., 2020), ensures it reflects the aerator's performance under standard conditions, allowing consistent comparisons between different equipment.

Adjusted Oxygen Transfer Rate (OTR_T)

The OTR_T adjusts the SOTR to specific pond conditions, considering a target dissolved oxygen level of 50% saturation, which is optimal according to literature to avoid hypoxia and stress (Boyd, 2015; Boyd, 2020; Nunes & Musig, 2013). First, we calculate OTR_{20}:

$$OTR_{20} = SOTR \times \frac{Cs_{100\%}(salinity\ ppt, 20°C) - Cs_{50\%}(salinity\ ppt, 20°C)}{Cs_{100\%}(salinity\ ppt, 20°C)}$$

Where:

- $Cs_{100\%}(salinity\ ppt, 20°C)$: oxygen saturation concentration at $20°C$ and pond salinity.
- $Cs_{50\%}(salinity\ ppt, 20°C)$: target oxygen concentration ($0.5 \times Cs_{100\%}$).

Since $Cs_{50\%} = 0.5 \times Cs_{100\%}$, the formula simplifies to:

$$OTR_{20} = SOTR \times 0.5$$

Then, we adjust for temperature to pond conditions (T) using the factor $\theta = 1.024$ (Sadek et al., 2020):

$$OTR_T = OTR_{20} \times \theta^{(T-20)}$$

The OTR_T is more relevant than SOTR for practical applications, as it reflects the actual aerator performance adjusted for the target dissolved oxygen level and the pond's operating temperature.

Standard Aeration Efficiency (SAE)

The **SAE** (Standard Aeration Efficiency) measures the aerator's energy efficiency, expressed as the amount of oxygen transferred per unit of energy consumed under standard conditions (Kumar et al., 2020; Sadek et al., 2020):

$$SAE = \frac{SOTR}{Power\ (kW)} \quad (kg\ O_2/kWh)$$

Where power in kW is calculated from the aerator's HP, using the conversion $1\ HP = 0.746\ kW$.

Total Oxygen Demand (TOD)

The **Total Oxygen Demand (TOD)** in a shrimp farm is calculated by summing the contributions from shrimp respiration and the pond's microbial activity (water column and bottom) (FAO, n.d.; Nunes & Musig, 2013). The pond's contribution is measured experimentally by summing the absolute amounts of oxygen consumed in the water column and bottom:

$$O_2\ consumption\ (water\ column) = \left(Initial\ water\ O_2 - Final\ water\ O_2\right)$$

$$O_2\ consumption\ (bottom) = \left(Initial\ bottom\ O_2 - Final\ bottom\ O_2\right)$$

These amounts are summed, multiplied by the corresponding volume of each pond component, and by a conversion factor (10^{-3}) to obtain the demand in kg/h. The total TOD is expressed in kg O_2/h and is used to determine the number of aerators needed:

$$N = \frac{TOD}{OTR_T}$$

Standard Financial Metrics

To evaluate the economic viability of the aerators, we use the following standard financial metrics (Engle, 2010; Engle, 2017; Jolly & Clonts, 1993).

Net Present Value (NPV)

The **NPV** (Net Present Value) measures the current value of net cash flows generated by an investment, discounted at an interest rate r:

$$NPV = \sum_{t=0}^{T} \frac{Cash\ flow_t}{(1+r)^t}$$

In the context of aerators, cash flows include the initial cost (negative) and annual savings (positive) generated by choosing one aerator over another. For savings growing with inflation g:

$$NPV = -\ Initial\ Cost + \sum_{t=1}^{T} \frac{Annual\ Saving \times (1+g)^t}{(1+r)^t}$$

This can be simplified as a growing annuity:

$$NPV = -\ Initial\ Cost + Annual\ Saving \times (1 + g) \times \frac{1-\left(\frac{1+g}{1+r}\right)^T}{r-g}$$

Payback Period

The **Payback Period** measures the time required to recover the initial investment through generated cash flows (undiscounted):

$$Payback\ Period = \frac{Initial\ Cost}{Annual\ Saving}$$

Internal Rate of Return (IRR)

The **IRR** (Internal Rate of Return) is the discount rate that makes the NPV equal to zero:

$$0 = \sum_{t=0}^{T} \frac{Cash\ flow_t}{(1+IRR)^t}$$

For uniform cash flows (with inflation):

$$0 = -\ Initial\ Cost\ + \sum_{t=1}^{T} \frac{Annual\ Saving \times (1+g)^t}{(1+IRR)^t}$$

The IRR must be solved numerically, but it indicates the investment's profitability: if $IRR > r$, the investment is profitable.

Profitability Index (PI)

The **PI** (Profitability Index) measures the ratio of the present value of benefits to the initial cost:

$$PI = \frac{Present\ Value\ of\ Benefits}{Initial\ Cost}$$

A PI greater than 1 indicates a profitable investment.

Return on Investment (ROI)

The **ROI** (Return on Investment) measures the annual return as a percentage of the initial cost:

$$ROI = \frac{Annual\ Saving}{Initial\ Cost} \times 100$$

These standard metrics provide a basis for evaluating and comparing aerator options (Engle, 2010; Engle, 2017; Jolly & Clonts, 1993), but must be adapted to the specific context of the shrimp farm, considering the total oxygen demand (TOD) and operating conditions.

Case Study: Analysis of Aerators in an Ecuadorian Shrimp Farm

Farm Operating Conditions

- **Total Area**: $1,000\ ha$
- **Annual Production**: $10\ ton/ha/year$, i.e., $10,000\ kg/ha/year$.
  - With 3 cycles of 4 months each: $3,333.33\ kg/ha/cycle$.
  - For $1,000\ ha$: $3,333,333\ kg/cycle$.
- **Shrimp Price**: $5\ USD/kg$.
- **Revenue per cycle**: $16,666,665\ USD/cycle$.
- **Annual Revenue**: $50,000,000\ USD/year$.

Environmental Conditions

- **Salinity**: $20\ ppt$.
- **Temperature**: $30 - 33°C$ (average $31.5°C$).
- **Pond Depth**: $1\ m$.

Aerator Characteristics

- **Aerator** 1:
  - Power: $3\ HP$.
  - $SOTR$: $1.4\ kg\ O_2/h$.
  - Initial Cost: $500\ USD$.
  - Durability: 2 years.
  - Maintenance: 30% more than Aerator 2.
- **Aerator** 2:
  - Power: $3.5\ HP$.
  - $SOTR$: $2.2\ kg\ O_2/h$.
  - Initial Cost: $800\ USD$.
  - Durability: 4.5 years.
  - Maintenance: Base cost ($50\ USD/year$).

Other Parameters

- **Energy Cost**: $0.05\ USD/kWh$.
  - Aerator 1: $3\ HP = 2.238\ kW$. Cost per hour: $0.1119\ USD/h$.
  - Aerator 2: $3.5\ HP = 2.611\ kW$. Cost per hour: $0.13055\ USD/h$.
- **Operating Hours**: 8 night hours per day $(2,920\ h/year)$.
- **Interest Rate**: 10%.
- **Annual Inflation**: 2.5%.
- **Analysis Horizon**: 9 years $(LCM\ of\ 2\ and\ 4.5)$.

Calculation of Total Oxygen Demand (TOD)

Oxygen Saturation

At $31.5°C$ and $20\ ppt$:

- $Cs_{100\%}(31.5°C, 20, ppt) = 6.55\ mg/L$ (value estimated by interpolation from standard tables).
- At 50% saturation (target level): $Cs_{50\%} = 3.275\ mg/L$.

Shrimp Respiration

At $31.5°C$, $20\ ppt$, average weight $10g$:

- Rate: $0.3436\ mg\ O_2/g/h$. Value obtained from table.
- Biomass: $3,333,333\ kg\ =\ 3,333,333,000\ g$.
- Demand: $1,145.33\ kg\ O_2/\ h$.

Pond Respiration

We calculate the absolute amounts of oxygen consumed in the water column and bottom, and sum them (method based on FAO, n.d.; Nunes & Musig, 2013):

- **Water Column**: Consumption of $3.275\ mg/L$ in $8h$. Rate: $4,093.75 kg\ O_2/h\ for\ 1,000\ ha$
- **Bottom**: Consumption of $1.6375\ mg/L$ in $8h$. Rate: $204.6875\ kg\ O_2/h\ for\ 1,000\ ha$.
- **Total Pond Respiration**: $4,298.4375\ kg\ O_2/h$.
- **Total Oxygen Demand (TOD)**:

$$TOD\ =\ 1,145.33\ +\ 4,298.4375\ =\ 5,443.7675, kg\ O_2/h$$

Calculation of OTR_T

We adjust $SOTR$ to $31.5°C$ and 50% target saturation (Sadek et al., 2020):

$$OTR_T = (SOTR\ \times\ 0.5) \times 1.024^{(31.5-20)} = (SOTR\ \times\ 0.5) \times 1.024^{11.5} \approx SOTR\ \times\ 0.5\ \times\ 1.3275$$

$$OTR_T = OTR_{20} \times 1.024^{(T-20)}$$

$$OTR_{20}\ =\ SOTR\ \times \frac{Cs_{100\%}(20ppt, 20°C) - Cs_{50\%}(20ppt, 20°C)}{Cs_{100\%}(0ppt, 20°C)} \times\ \alpha\ \times\ \beta$$

Adjust for temperature:

$$1.024^{(31.5-20)} = 1.024^{11.5} \approx\ 1.3275$$

- Aerator 1 ($SOTR = 1.4\, kg\, O_2/h$):

$$OTR_{T1} = (1.4 \times 0.5) \times 1.3275 = 0.7 \times 1.3275 \approx 0.9293, kg\, O_2/h$$

- Aerator 2 ($SOTR = 2.2\, kg\, O_2/h$):

$$OTR_{T2} = (2.2 \times 0.5) \times 1.3275 = 1.1 \times 1.3275 \approx 1.4603, kg\, O_2/h$$

Number of Aerators

$$N = \frac{TOD}{OTR_T}$$

- Aerator 1: $N_1 = \frac{5,443.7675}{0.9293} \approx 5,858$
- Aerator 2: $N_2 = \frac{5,443.7675}{1.4603} \approx 3,728$

Operating Costs

- **Annual energy cost per aerator**:
  - Aerator 1: $326.75\, USD/year$
  - Aerator 2: $381.21\, USD/year$.
- **Total annual energy cost**:
  - Aerator 1: $326.75 \times 5,858 = 1,913,746.50\, USD/year$.
  - Aerator 2: $381.21 \times 3,728 = 1,421,189.88\, USD/year$.
- **Initial cost**:
  - Aerator 1: $5,858 \times 500 = 2,929,000\, USD$.
  - Aerator 2: $3,728 \times 800 = 2,982,400\, USD$.
- **Annual maintenance**:
  - Aerator 1 ($65\, USD/year$): $65 \times 5,858 = 380,770\, USD/year$.
  - Aerator 2 ($50\, USD/year$): $50 \times 3,728 = 186,400\, USD/year$.
- **Annualized replacement**:
  - Aerator 1: $\frac{2,929,000}{2} = 1,464,500\, USD/year$.

- Aerator 2: $\frac{2,982,400}{4.5} = 662,755\ USD/year$.

- **Total annual cost**:
  - Aerator 1: $1,913,746.50 + 380,770 + 1,464,500 = 3,759,016.50\ USD/year$.
  - Aerator 2: $1,421,189.88 + 186,400 + 662,755.56 = 2,270,345.44\ USD/year$.

- **Standard Aeration Efficiency (SAE)** (Kumar et al., 2020; Sadek et al., 2020):
  - Aerator 1: $SAE_1 = \frac{1.4}{2.238} = 0.6256\ kg\ O_2/kWh$.
  - Aerator 2: $SAE_2 = \frac{2.2}{2.611} = 0.8426\ kg\ O_2/kWh$.

- **Cost per kg of Oxygen Transferred (based on energy cost)**:
  - Aerator 1: $O_2/year = 0.9293 \times 2,920 = 2,713.556\ kg\ O_2/year$.
    - $Cost/kg = \frac{326.75}{2,713.556} \approx 0.1204\ USD/kg\ O_2$
  - Aerator 2: $O_2/year = 1.4603 \times 2,920 = 4,263.676\ kg\ O_2/year$.
    - $Cost/kg = \frac{381.21}{4,263.676} \approx 0.0894\ USD/kg\ O_2$

Relative Analysis

- **Cost as a percentage of revenue**:
  - Aerator 1: $\frac{3,759,016.50}{50,000,000} \times 100\% = 7.52\%$
  - Aerator 2: $\frac{2,270,345.44}{50,000,000} \times 100\% = 4.54\%$
  - Difference: 2.98% $(equivalent\ to\ 1,488,671.06\ USD/year)$

Savings from Aerator 2

- **Annual Saving**: $3,759,016 - 2,270,345 = 1,488,671\ USD/year$.
- **Additional Initial Cost**: $2,982,400 - 2,929,000 = 53,400\ USD$.

Break-Even Point and Profitability Coefficient k

Variable Definition

- $TOD: 5,443.7675\ kg\ O_2/h$
- $OTR_{T1} = 0.9293$
- $OTR_{T2} = 1.4603$
- $P_1 = 500$
- $P_2 = 800$
- $N_1 = 5,858$
- $N_2 = 3,728$
- $C_{E1,annual} = 326.75$
- $C_{E2,annual} = 381.21$
- $M_1 = 65$
- $M_2 = 50$
- $L_1 = 2$
- $L_2 = 4.5$
- $T = 9$
- $r = 0.1$
- $g = 0.025$

Relationship with Water Quality

TOD is derived from water quality equations (FAO, n.d.; Nunes & Musig, 2013):

$$TOD = Shrimp\ Respiration + Pond\ Respiration = 5,443.7675, kg\ O_2/h$$

Shrimp respiration depends on biomass, temperature, and salinity, while pond respiration is calculated by summing consumption in the water column and bottom. TOD determines N, affecting operating and investment costs (Engle, 2010; Jolly & Clonts, 1993).

Break-Even Point (Price of P_2 to equalize annual costs)

The break-even point occurs when the total annual cost of both aerators is equal:

$$C_{total,1} = C_{total,2}$$

Substituting:

$$N_1 \times C_{E,annual} + N_1 \times M_1 + \frac{N_1 \times P_1}{L_1} = N_2 \times C_{E,annual} + N_2 \times M_2 + \frac{N_2 \times P_2}{L_2}$$

Substitute $N_1 = \frac{D}{SOTR_1}$, $N_2 = \frac{D}{SOTR_2}$:

$$\frac{D}{OTR}_{T1}\left(C_{E,annual} + M_1 + \frac{P_1}{L_1}\right) = \frac{D}{OTR}_{T2}\left(C_{E,annual} + M_2 + \frac{P_2}{L_2}\right)$$

Divide both sides by D:

$$\frac{1}{OTR}_{T1}\left(C_{E,annual} + M_1 + \frac{P_1}{L_1}\right) = \frac{1}{OTR}_{T2}\left(C_{E,annual} + M_2 + \frac{P_2}{L_2}\right)$$

Multiply both sides by $OTR_{T1} \times OTR_{T2}$:

$$OTR_{T2}\left(C_{E,annual} + M_1 + \frac{P_1}{L_1}\right) = OTR_{T1}\left(C_{E,annual} + M_2 + \frac{P_2}{L_2}\right)$$

Isolate P_2:

$$OTR_{T2}\left(C_{E,annual} + M_1 + \frac{P_1}{L_1}\right) = OTR_{T1}\left(C_{E,annual} + M_2\right) + OTR_{T1}\frac{P_2}{L_2}$$

$$OTR_{T1}\frac{P_2}{L_2} = OTR_{T2}\left(C_{E,annual} + M_1 + \frac{P_1}{L_1}\right) - OTR_{T1}\left(C_{E,annual} + M_2\right)$$

$$P_2 = \frac{L_2}{OTR_{T1}}\left[OTR_{T2}\left(C_{E1,annual} + M_1 + \frac{P_1}{L_1}\right) - OTR_{T1}\left(C_{E2,annual} + M_2\right)\right]$$

$$P_2 = \frac{4.5}{0.9293}\left[1.4603\left(326.75 + 65 + \frac{500}{2}\right) - 0.9293(381.21 + 50)\right]$$

$$P_2 = \frac{4.5}{0.9293}[1.4603 \times 641.75 - 0.9293 \times 431.21]$$

$$P_2 = \frac{4.5}{0.9293}[937.14 - 400.74] = \frac{4.5}{0.9293} \times 536.40 \approx 2,599.37, USD$$

The break-even price for Aerator 2 would be $2,599.37\, USD$. Since its actual cost is $800\, USD$, it is much more advantageous.

Profitability Coefficient k

$$k = \frac{PV(Savings)}{Additional\ Cost}$$

- **Additional Cost**:

  $N_2P_2 - N_1P_1 = 3,728 \times 800 - 5,858 \times 500 = 2,982,400 - 2,929,000 = 53,400\, USD$

- **Annual Saving**:

$$C_{total,1} - C_{total,2} = 1,488,671.06\, USD/year$$

- **Present Value of Savings (PV)**: Using the growing annuity factor $F = 5.5555$:

$$PV(Savings) = 1,488,671.06 \times 5.5555 \approx 8,266,969.79, USD$$

- **Calculation of k**:

$$k = \frac{8,266,969.79}{53,400} \approx 154.81$$

Relationship with Standard Financial Metrics

- $PI = k = 154.81$ (Engle, 2017)
- $NPV = PV(Savings) - Additional\ Cost = 8,266,969.79 - 53,400 = 8,213,569.79\, USD$

  The high efficiency (SAE) of Aerator 2 $(0.8426\ vs\ 0.6256)$ translates into a positive and high NPV (Kumar et al., 2020; Sadek et al., 2020)

- **IRR**: solving $0 = -\ Additional\ Cost + \sum_{t=1}^{9} \frac{Annual\ Saving \times (1.025)^t}{(1+IRR)^t}$ Given the high k, the IRR will be extremely high, much greater than the 10% discount rate. Approximately $1,488,671/53,400 \approx 2788\%$.
- **Payback Period (Simple)**: $\frac{Additional\ Cost}{Annual\ Saving} = \frac{53,400}{1,488,671.06} \approx 0.0359\ years \approx 13.1\ days$
- **ROI (Simple Annual)**: $\frac{Annual\ Saving}{Additional\ Cost} \times 100\% = \frac{1,488,671.06}{53,400} \times 100\% \approx 2,787.77\%$.

Conclusion: General Equilibrium, Opportunity Cost, and the Crisis in the Ecuadorian Shrimp Industry

The analysis, based on the **Total Oxygen Demand (TOD)** of $5,443.7675\ kg\ O_2/h$, calculated by summing the absolute contributions of oxygen consumed, demonstrates that Aerator 2 is significantly more profitable, reducing total annual costs by 39.5% $(1,488,671.06\ USD/year)$. The profitability coefficient $(k = 154.81)$ indicates that for every additional dollar invested in Aerator 2, $154.81\ USD$ are generated in net present value savings (Engle, 2017). The opportunity cost of choosing Aerator 1 is $8,266,969.79\ USD$, reflecting the savings lost by not opting for Aerator 2 (Engle, 2010; Jolly & Clonts, 1993; Tveteras, 2009).

Relationship with Opportunity Cost and General Equilibrium

The opportunity cost of opting for Aerator 1 is the present value of the savings lost with Aerator 2 $(8,266,969.79\ USD)$. Choosing Aerator 1, with an $OTR_{T1} = 0.9293$, requires more units ($5,858\ vs.\ 3,728$ for Aerator 2), increasing operating costs and disrupting the general equilibrium of the shrimp farm's interconnected markets (Asche et al., 2021; Valderrama et al., 2023).

Implications

Choosing Aerator 2 satisfies the TOD more efficiently (higher SAE), mitigating the impact of shrimp price volatility and reducing opportunity cost (Boyd, 2015; Kumar et al., 2020; The Fish Site, 2021). This analysis, adjusted to correctly sum the oxygen consumption contributions and include the effect of temperature on OTR_T (Sadek et al., 2020), reinforces the importance of considering actual oxygen demand and operating conditions to make sustainable financial decisions in the Ecuadorian shrimp industry (Engle, 2010; Merino et al., 2024).

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