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Mathematical principles of production management and robust layout design: Part II. Upscaling to a 1000-ton/year recirculating aquaculture system (RAS)

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ABSTRACT

The design and management of a recirculating aquaculture system (RAS) is crucial for the farm's economic survival. In a previous paper (Part I of this study), a model was developed. The current paper extends the principles developed in Part I by (1) addressing a larger-scale RAS, (2) addressing the layout positioning problem, (3) integrating a robust 6σ design into the optimization problem. A queuing model and a solvable nonlinear constrained optimization problem including the 6σ robust design were developed and validated. The design criteria were: (1) turnover ≥1000 ton/year, (2) 7 days quarantine, i.e., at least 7 days between arrivals of two successive fish batches, (3) fish biomass density ≤55 kg/m^3, (4) three growth phases, (5) neither fish-sorting nor batch-splitting events allowed, and (6) a robust design to accommodate two species—seabream and seabass grouper, with different growth rates. Decision variables were: (1) number of culture tanks, (2) fingerling arrival frequency, (3) number of fingerlings per batch, (4) number of days in a growth phase, (5) timing of grading and sorting criteria on the production lines, (5) standing biomass in the entire system, which is the actual biomass load on the biofilters, (6) feed amount per day.

The optimal layout was: 13 culture tanks in each of the three growth phases (39 tanks total). Optimal parameters included: arrival frequency—a single fish batch into the system every 7 days, 91 days in each phase; growth up to 77, 233, and 468 g in successive growth phases. Optimal values satisfied the criteria of biomass density below 50 kg/m^3 and culture tank utilization above 99%. Expected production was 1000 ton/year. The proposed layout can accommodate different fish species—here, seabream and grouper—under the same culture volume, density, and schedule, but with different growth rates. Increasing the desired biomass density from 50 to 60 kg/m^3 advances expected production to 1335 ton/year. The numerical values reflect local aquatic conditions, but the proposed methodology can be applied anywhere.

1. Introduction

Recirculating aquaculture systems (RASs) save on water, use less land, reduce waste-stream effluent, and produce year-round with a high degree of product traceability. An intensive RAS depends on sustaining high-quality water and low fish stress, which requires efficient management of the multi-unit biological processes and/or operations involved. Its profitability relies on maximizing fish biomass per unit volume and therefore, poor management has been cited as the primary reason for failure of several RAS ventures (Libey and Timmons, 1996; Summerfelt, 1996; Timmons et al., 2001). However, no decision-support tool incorporating optimization and uncertainty has been reported in the design of intensive large-scale mass-production RASs (Seginer and Halachmi, 2008). Sets of equations and operational research (OR) tools have being developed (see a list in Part I of this study, Halachmi, 2012), but if validation was performed at all, they referred to types or intensities of aquaculture systems, smaller-scale pilot or research facilities, than that dealt with here (Seginer and Halachmi, 2008).

One reason for the lack of model applications in RASs might be the need to quantify the inherent **uncertainty** in this system. During the lifetime of an aquaculture farm—extending over decades—there may be a degree of diversity in fish growing time for various reasons: (1) ever-changing genetic material; (2) changes in feedstuff; (3) changes in fish-handling practice by the farm staff; (3) improvements in biofilters, oxygen supply, and other factors that affect water quality; (4) stress, illness and fish mortality; (5) possible changes in the timing of fingerling arrivals, because each hatchery has its own priorities and schedules; (6) changes in the timing of fish deliveries to market. Thus, RAS design and operation involve '*decisions under uncertainty*'. Other fields, from telephone networks to warehousing, and from manufacturing (Cooper, 1981;

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Nomenclature

Tank	circular–conical fish culture volume, made of concrete, plastic, fiberglass, etc.
T	yearly turnover (kg or ton per year); the desired yearly turnover (T) was 1000 ton/year
λ and μ	arrival and departure rates, respectively (batches/year); the preferred arrival frequency of fingerlings was one batch per week ($\lambda = 52$)
S_i	the growth period in growth phase i
$\sum S_i$	the total growth period throughout all of the phases, from a fingerling entering the farm until its departure to the fish market $\sum S_i = 273$ days
t	fish days in the system (not age)
ρ	expected utilization of a service facility such as a culture tank
c	number of culture tanks
c_i	number of culture tanks in growth phase i. A layout of three growth phases is termed a c_1, c_2, c_3 system. e.g., a 1, 8, 20 system comprises 1, 8, and 20 culture tanks in the 1st, 2nd, and 3rd growth phases, respectively
D	fish biomass stocking density (kg/m^3)
D_i	maximum biomass at the end of growth phase i. Design criteria were: *Seabram*: $D_1 \leq 30\,\text{kg/m}^3$; $D_2 \leq 55\,\text{kg/m}^3$; $D_3 \leq 55\,\text{kg/m}^3$; *Grouper*: $D_1 \leq 40\,\text{kg/m}^3$; $D_2 \leq 60\,\text{kg/m}^3$; $D_3 \leq 60\,\text{kg/m}^3$ in three successive growing phases
V	volume of a culture tank (m^3)
V_i	culture tank volume in growth phase i
N	number of purchased fingerlings, also called batch size
N_f	final number of marketed fish from a batch Ni – number of fish in a batch at the end of growth phase i
B	fish body weight (kg)
B_f	the final body weight at selling time
B_i	fish body weight at the end of growth phase i
$B_{\text{fingerling}}$	is the fingerling weight at purchase, e.g., for 2-g fingerlings: $B_i = B_{\text{fingerling}} + G_r \sum S_i$. The market demands $B_3 = B_f = 0.4$ kg for both species. However, sometimes there is a demand for a bigger product: 0.468 and 0.627 kg for seabream and grouper, respectively
G_r	average growth rate; $G_r = B_f / \sum S_i$ (kg/day), neglecting biomass at purchase – $B_{\text{fingerling}}$ survival rate, 0.9. This study assumes 10% mortality. The design criteria include: (1) turnover of 1000 ton/year, (2) 52 batches/year, (3) a specified biomass density, (4) three growth phases, such as: "1, 8, 20" layout, (5) no batch splits, (6) robust design for two species—seabream and grouper
OR	operational research
S.T.	"such that", or "subject to" the constraints. This term 'S.T.' refers to extrema with constraints in mathematical optimization
σ	refers to standard deviation. Standard deviation or variance, σ^2, is a measure of dispersion of a set of data a natural "shift" in a parameter around the mean value, μ, of these data. Design for 6σ is 6σ-based lower and upper specifications that tackle a natural "shift" in a parameter

Table 1
Average growth of the two species: coefficients of a second-degree polynomial $P(X)$.

	P_2	P_1	P_0
B[a] Grouper (Seabass)	+0.0052	+0.874	+1.0
B Gilthead (Seabream)	+0.0048	+0.401	+1.0

[a] B is the fish's live weight in grams. $B = P_2 t^2 + P_1 t + P_0$, where t is days in the system (not fish age), ranging from 0 to 350 days.

Gross, 2008) to dairy farming (Halachmi et al., 2000, 2003), deal with **uncertainty** in their systems but, curiously, models dealing with uncertainty have rarely been applied to intensive recirculating aquaculture design.

Application of a simulation model was reported by Halachmi et al. (2005) but with no analytical model and therefore, no search for a global optimum was executed at that time. An application of queuing theory was reported by Halachmi (2007). However, that study (1) did not integrate optimization into the set of queuing equations, and ended with an analysis of a "what-if?" scenario, rather than a complete optimization methodology. A more recent study (Part I of this study: Halachmi, 2012) integrated optimization, but (2) dealt with the design of a smaller facility that would handle 250 ton/year, (3) applied predefined parameters, set by the farmers, such as fish arrival frequency—once per month—and 90-m^3 culture tanks that reduced the space of feasible solutions, (4) did not integrate its reliability analysis (6σ robust design) into the optimization solver, and (5) did not address the location issue, a crucial aspect in every layout design. The current study might serve to bridge the gap.

In modern agriculture, farms are getting bigger (Timmons et al., 2001). Under this study's conditions, a 250-ton RAS is expected to be above the break-even (BE) scale of production at which total production cost/unit and price are in equilibrium for the coming 5 years. Later on, an expected rise in feed costs, labor, energy and imported cheap fish might push the BE further. Therefore, addressing a larger RAS is of interest.

The aims of the present study were: (1) to combine the previously developed queuing model with optimization and robust design, (2) to set up an example—to design a 1000-ton/year RAS with an optimal number of culture tanks, balance production lines, and determine optimal arrival frequency, batch size, number of culture tanks, standing biomass, and facility allocation and location.

2. Materials, methods, model formulation and analysis

2.1. Local aquatic conditions and fish data used for the design

Fish growth combines many local conditions, such as water quality and water temperature, feed stuff, genetic lines, handling, etc. Grouper (seabass) growth data were provided by the equipment supplier based on previously designed systems. Gilthead seabream (*Sparus aurata*) growth data from 24 fish batches, each comprising an average of 42,111 fish (standard deviation 3,355), were recorded over 4 years, from Feb 2007 to Nov 2010, at the Ardag "Pilot" farm, Eilat (for further details, see Halachmi, 2007; Mozes, 2004; Mozes et al., 2005). At the new facility, the farmer's intention was to raise the water temperature in order to speed up fish growth rate. Therefore, for design purposes, only the upper tenth, i.e., 10% fastest-growing batches were selected. These fish can reach a target body weight of 468 g (seabream) or 627 g (grouper) within 39 weeks (273 days). Curve fitting yielded the growth functions presented in Fig. 1. The parameters of average weight were expressed as a second degree polynomial $P(X)$ that gave the best least-squares fit to the fish weight (B) data. In Table 1, P is a row vector of length 2 + 1 containing the polynomial coefficients in descending powers, $B = P_2 t^2 + P_1 t + P_0$, where t is days in the system (not age), and ranges