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Mathematical principles of production management and robust layout design: Part III. 2500-ton/year fish farming in marine net cages[☆]

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ABSTRACT

Fish production in marine netcages is expanding rapidly in many parts of the world. Nevertheless, production planning and layout design tools still rely on rule of thumb, spreadsheets, local experience and practices handed down through the generations. An integrated model (queuing, optimization and simulation were linked together) was developed. The solution finds the values of decision variables to maximize yearly production.

The concept was that a single netcage can be seen as a “server” in which neither a “queue” (over-holding of fish), nor an idle netcage is allowed. A marine fish farm can then be seen as a queuing network, and a queuing network-based management model was developed.

Growth data of 40 batches of fish, each batch comprising on average 180,000 fish (std 50,000), were recorded over an experimental period of 4 years.

The model inputs were (1) the empirical fish growth rates (2) the given space for netcages, (3) preferred netcage holes, netcage depth and netcage diameter, (4) fingerling supply limitations, (5) market timing, and (6) Preferred market-size fish at the farm gate. The model outputs were: (7) optimal fingerling arrival frequency, (8) optimal number of fingerlings in a batch, (9) number of days in each culture netcage, (10) grading and sorting criteria along the production line, and (11) optimal facility allocation (number of netcages for each growing phase). Model validity was statistically tested and was not rejected within the 95% confidence level. The model application results with 4 netcages in the 1st growing phase, 8 netcages in the 2nd growing phase and 16 netcages in the 3rd growing phase (so called “4,8,16 layout”) gave the following optimal operating parameters: arrival of a batch every 30 days; 122 days in each successive growth phase. The optimal values satisfied the biomass density criterion of less than 25 kg m^{-3} and the netcage utilization criterion of never below 99%. Expected production was 2403 ton year^{-1} (vs. the current 686 ton year^{-1}). The enterprise owners decided to adopt the model results and the system is now being built according to the 4,8,16 design.

1. Introduction

Production planning is among the most important managerial activities in commercial fish farming. Queuing theory has contributed to managerial activities in wide range of fields, from telephone networks to warehousing, car manufacturing and dairy farms (Cooper, 1981; Halachmi et al., 2000, 2003). Curiously, it has rarely been applied to marine netcages.

Fish farms in marine net cages can be operated by: (1) stocking fingerlings at given time intervals into the 1st phase grow-out system; (2) feeding the fish, then grading, sorting and transferring the fish to larger culture volumes, and (3) continuous grading and harvesting of market-size fish, or alternatively sending the entire fish batch to market after a predefined time without any size sorting. The main planning issues are: deciding on the optimal number of fingerlings to purchase, estimating population growth and resource requirements, and choosing the optimal harvesting plans and optimal batch transfer to a larger culture volume in order to maximize profits from the operation.

Modeling fish harvesting requires both equations describing fish growth, and algorithms determining the optimal harvest size at any future time. Three model approaches have been described. (Summerfelt et al., 1993) calculated the number of fish available for harvesting by assuming that fish length follows a normal distribution; thus, the number of harvested individuals was determined from the capacity limit of the farm. In the second approach, the size distribution of individuals was considered a discrete, time-varying Markov process in which the number of individuals in each size class could be calculated. The optimal harvesting of individuals from various size classes was determined by dynamic

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[☆] Part I and Part II of this article have already been published in Volume 50, Pages 1–19 (September 2012).

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Symbols and terms

Netcage	a fish culture volume, made of a net and located in the sea
λ and μ	fish arrival and departure rates, respectively (batches year^{-1})
S	growth period in a netcage (years)
S_i	growth period in growing phase i
T	fish age (days in sea)
$y(t)$	fish body weight on any given day
ρ	expected utilization of a netcage
P	number of sub-batches formed from a batch
V	netcage volume (m^3)
V_i	netcage volume in growing phase i. In Ashdod harbor, 18 netcages of 2900 m^3 each and 11 netcages of 2000 m^3 each can fit along the breakwater. Total number of netcages is 29
c	number of netcages
c_i	number of netcages in growing phase i; e.g. c_1,c_2,c_3 = 4,8,16 stands for 4 netcages in the 1st growing phase, 8 netcages in the 2nd growing phase, and 16 netcages in the 3rd phase
D	fish biomass stocking density (kg m^{-3})
D_i	biomass in growing phase i
N_f	final number of fish in a batch
N_i	number of fish in a batch in growing phase i
B_f	final body weight of a fish (kg)
B_i	body weight of a fish (kg) in growing phase i
S.T.	"Subject to the constraints". This term refers to Extrema with Constraints in mathematical optimization
The decision parameters	$N, c_1, c_2, c_3, S_1, S_2, S_3, P_1, P_2, P_3$

programming (Leung et al., 1990; Leung and Shang, 1989; Sparre, 1976). The third approach is a variation of linear programming (LP) and dynamic programming (DP). LP has been frequently used in production planning in aquaculture production, such as for cost minimization in oyster farms (Lipschultz and Krantz, 1980) and profit maximization in prawn farms (Shaftel and Wilson, 1990; Wilson and Schaftel, 1991), multicycle and multiponds operation of shrimps farms (Yu and Leung, 2005; Yu et al., 2006), salmonid hatcheries (Johnson, 1974) and salmonid grow-out farms (Gates et al., 1980; Varvarigos and Home, 1986). We refer to (Forsberg, 1996) who discussed LP vs. DP in the aquaculture context and indicated that neither LP nor DP are adaptable to all aquaculture systems. Other approaches include modeling sinusoidal marketing conditions (Seginer and Halachmi, 2008) and operational research (Weintraub et al., 2007). Halachmi (2007) reported on a single application of queuing theory but it did not combine simulation optimization or address marine netcages. It 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, 2012a) integrated optimization, but (1) dealt with the design of a smaller facility that would handle 250 ton/year, (2) applied predefined parameters, set by the farmers, such as fish arrival frequency—once per month that reduced the space of feasible solutions. Part 2 (Halachmi, 2012b)), introduced reliability analysis (6σ robust design) into the optimization solver, and addressed the location issue. But both parts, Halachmi (2012a,b) developed models to inland recirculating aquaculture system (RAS). Inland RAS operation mode is considerably different since the RAS limitation is the biofilter capacity and RAS's water temperature and water quality can be controlled, parameters that are incontrollable in marine netcages. The integrated model has to be adjusted accordingly. The current study might serve to bridge the gap.

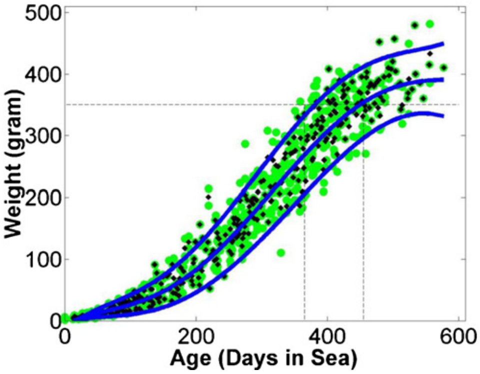

Fig. 1. Quantifying fish growth functions. Forty fish batches were sampled 1006 times during their growing period. Each point indicates the measured average weight of a fish batch—real, not simulated data. Three types of fish growth curves can be identified: fast growers (y_{max}), slow growers (y_{min}) and average growers (y_{ave}). On fig.: labels should be: weight (g); age (days in sea).

Therefore, the current study combines queuing-network and simulation-optimization models, with adaptation to marine netcages, with the aim of optimizing stocking numbers and harvesting schedules. This is a new approach to optimal production planning in marine netcages. Therefore, **the goal** of the present study was to find: the optimal arrival frequency, the optimal batch size of fingerlings, optimal grading criteria along the growth period, and optimal facility allocation to clear production-line bottlenecks and increase biomass output. The application of queuing theory is particularly appropriate for marine netcages, where optimal design and management are crucial to the success of the aquaculture enterprise.

2. Materials and methods

The main contribution of this study was the development of the model presented in Section 3. The fish data (2.1) described herein were used (1) as model inputs, and (2) to demonstrate the model's applicability, scope and focus. Perhaps, the fish data reflect local aquatic conditions but the amount of data and data-collection procedures, simulation (2.2), optimization (2.3), statistical tests (2.4) and validation (3.3) procedures are all applicable also elsewhere.

2.1. Fish growth: data acquisition

Data from 40 batches of fish, each comprising on average 180,000 fish (std 50,000), were recorded during an experimental period of 4 years from September 2005 to November 2008. The netcages were located at Ashdod harbor on the Mediterranean Sea. The average sea water temperature was 24.1 °C (std 4.2), with maximum 31.5 °C (August) and minimum 16.5 °C (January). The fish species was gilthead seabream (*Sparus aurata*). Dietary nutrition values were as reported previously (Lupatsch, 2004; Lupatsch and Kissil, 1998; Lupatsch et al., 1997, 1998, 2003). The 40 fish batches were sampled 1006 times during their growth period. A fish enters the system at an average weight of 2 g. Fast growers reached the target body weight of 350 g within 365 days, and for slow growers, 450 days was not always enough (Fig. 1). Curve fitting (Fig. 1) generated the following growth functions