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Optimal operation policy for a sustainable recirculation aquaculture system for ornamental fish: Simulation and response surface methodology

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ABSTRACT

Recirculating aquaculture systems (RAS) require a large investment in construction, equipment and energy. To ensure sufficient return on these investments, RAS operations must be managed meticulously. RAS managers must consider numerous factors related to the biological traits of the fish, logistics, seasonal market demand, and livestock management. RAS that specialize in ornamental fish are faced with particular challenges in that a given species of fish may actually yield several different "products," distinguished, for example, by color, which can be sold at different sizes for different prices. RAS managers need to consider the market prices of different-sized fish in the light of their production costs (cost of food and space, dependent on time in the system). The current study aims to develop an optimization model for the operations management of RAS specializing in ornamental fish. The objective of the model is to maximize annual profit. The methods used include: a general simulation model, built in Arena 11.0®, that seeks to mimic the studied system; an optimization procedure based on response surface methodology (RSM), including design of simulation experiments, stepwise regression (in SPSS® 11.0), and a nonlinear objective function and constraints solved with MATLAB®. The method is demonstrated in a case study—a RAS on Kibbutz Hazorea, Israel, raising ornamental koi fish (*Cyprinus carpio*).

1. Introduction

1.1. Recirculating aquaculture system

Aquaculture—the farming of fish and shellfish in a controlled environment—is a sector of the agriculture industry that is growing rapidly as it strives to satisfy increasing public demand for seafood and ornamental fish. Nonetheless, as the industry continues to grow so does public concern regarding its sustainability. A relatively new way of addressing this issue lies in the establishment of recirculating aquaculture systems (RAS), namely, indoor tank systems with controlled environments in which most of the water is reused after undergoing treatment. These systems, which first appeared in the 1970 s, constitute an alternative to the traditional method of growing fish outdoors in open ponds and raceways. One of the most important benefits of RAS production is the generation of high-quality water suitable for reuse, since to maximize efficiency RAS are designed to discharge as little water as possible each day. Another not less important benefit is land conservation, which is achieved by raising the fish at high densities.

Despite the benefits of RAS, a number of issues need to be addressed to ensure not only the sustainability but also the profitability of RAS. The operation of these systems can be challenging for a number of reasons. Firstly, most treatment methods applied within the framework of RAS achieve only partial water purification, since in comparison with the treatment methods in extensive ponds, they have limited ability to remove nitrates and organic matter (Van Rijn, 1996).

1.2. Properties of the problem

As for the profitability of RAS, recirculating systems require substantial investment in facilities, equipment and energy. To achieve a favorable return on investment (ROI) and remain profitable, meticulous management is required, and the engineering, biological and economic aspects of RAS operation have to be optimized (Halachmi, 2006). RAS managers must consider numerous factors related to the biological traits of the fish, logistics, seasonal mar-

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ket demand, and livestock management. RAS that specialize in ornamental fish are faced with particular challenges in that a given species of fish may actually yield several different "products," distinguished, for example, by color, which can be sold at different sizes for different prices. RAS managers need to consider the market prices of different-sized fish in the light of their production costs (cost of food and space, dependent on time in the system). The current study aims to develop an optimization model for the operations management of RAS specializing in ornamental fish.

1.3. Research objective

The main objective of the current research was to determine an effective production planning and operation policy under a given set of conditions for the production in a RAS of multiple ornamental fish products, in order to maximize annual profit. Such a policy was established by constructing a generic method that combines analytical techniques and extensive modular simulations, as described below.

In the literature review, we discuss the importance of operational management for RAS and we review some of the known techniques for RAS management, analytical optimization techniques, simulation modeling and simulation-based optimization techniques. In Section 3, we describe and formulate the problem of the current study. Sections 4 and 5 contain methods and results, respectively, and Section 6 presents the discussion. In Section 7, we end with conclusions and recommendations for optimal RAS management.

2. Literature review

2.1. Design and operational management for RAS

Optimization models developed for RAS must focus on both strategic/design and operation problems because, throughout the lifetime of a RAS, the RAS manager is called upon to make both strategic and operational decisions. Strategic decisions include: water volume for growing the fish, design and layout of culture tanks, type and size of biological filters, type of fish, and feeding technique and frequency. These decisions are made according to market demand, price, level of intensity (growth density) and budget. Operational decisions include: size and type of fish to market, fingerling size, batch size, stocking density, grading frequency, cleaning frequency, and environmental and temperature control. In a RAS, as in any industrial production facility, the daily operation-level decisions are dependent on the strategic decisions. Conversely, appropriate operational management provides flexibility at the strategic level. For instance, appropriate water treatment promotes a rapid growth rate and a high carrying capacity, which enables demand to be filled in high-market-price seasons. Each decision taken must consider both biological and economic factors and their effects on the main production process.

A number of different scenarios and models have been proposed for RAS design. Losordo and Hobbs (2000) proposed a design method implemented via spreadsheets to estimate the required flow rates, carrying capacity, and biofilter size for the RAS. Halachmi (2007) developed a model based on queuing theory for the optimal design and layout of a RAS for edible fish. The model determined the required arrival frequency and batch size of new batches of fingerlings. Two different queuing networks were analyzed to estimate the effect of several variables, such as initial size of fingerlings and fish growth function, on the number of fish sold per year. Both these models for RAS design for edible fish production (Losordo and Hobbs, 2000; Halachmi, 2007) addressed design and layout rather than management.

Several optimization models have recently been proposed for specific operation parameters in RAS: microbial resources (microorganisms in the biofilters in a RAS for shrimp) (Brown, 2013), oxygen supply (Seginer and Mozes, 2012), and stocking density in different seasons (Villanueva et al., 2013). In addition, Forsberg (1996) developed a multiperiod linear programming model to determine the optimal number of fry to transfer into the grow-out system, to estimate population growth and production costs, and to determine the optimal harvesting schedule for various size classes for maximal profit of the operation.

2.2. Simulation modeling

There is general agreement that simulation-based solution approaches are superior to analytical models for investigating complex stochastic systems (Wang and Chatwin, 2005), including production planning and inventory-system problems. Simulation-based approaches are preferred because an analytical model covering all stochastic and nonlinear dependencies of a complex problem is likely to be so complex that the solution will take more than an acceptable amount of time. The input data for the simulation are based on a real system (Law and Kelton, 1991), and the output of the simulation is defined as a response that is a function of the input variables (Dengiz and Akbay, 2000). Although a number of simulation models have been developed to test how different RAS would work in different situations, the simulation models for aquaculture systems have tended to focus primarily on biological aspects or even on a combination of biological and engineering aspects but very few have also taken management aspects into account. Jamu and Piedrahita (2002) developed simulation models for organic matter and nitrogen outputs in integrated aquaculture systems. One of the first models that did address management considerations was that of Ernst et al. (2000), who developed decision support software for design and management planning that simulates physical, chemical and biological unit processes. The proposed software was applicable for different aquaculture production facilities but was not designed specifically for a RAS. Another drawback of the study was that the authors applied the software to a limited set of fish types but did not validate it. Halachmi et al. (2006,2005) have worked extensively on simulation models that do take management considerations into account: they determined the optimal layout and management of a RAS for hybrid striped bass. Their mathematical simulation for the RAS took into account the growth rate and flow of fish through the RAS facilities (Halachmi et al., 2005). The input variables that represented management aspects for that RAS included: initial weight and target weight, mortality, time between batch arrivals, number of fish per batch, and grading time. The analyzed output was performance in terms of yearly turnover, stocking density, and tank and biomass utilization. That model, which can serve as a decision support tool for RAS managers, was suitable only for edible fish (hybrid striped bass) and is not applicable for ornamental fish. Halachmi (2012a, 2012b, 2013) then continued the work with an extensive mathematical study of a robust layout for the design and production management of an effective RAS. His model incorporated computer simulation, queuing theory methods and mathematical formulations. However, the models of Halachmi (2012a, 2012b,2013) were developed for the production of edible fish and are therefore not entirely applicable to ornamental fish, which are characterized, for example, by different market sizes and hence different prices, seasonal price variations and a lower biomass density.

In summary, most of the models developed to date have been formulated for edible fish, which are raised to a single market size and sold as a batch. In contrast, ornamental fish are sold in a variety of sizes, colors and shapes at different production stages and