Integration of process planning and scheduling for aquaculture

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Abstract

Aquaculture rotation is a continuous operation in which harvesting decisions affect factors such as payoff, product size/growth, and the starting of new crops. To maximize overall returns, a manager has to balance the returns from cycling a new crop after harvesting the current one. The situation becomes more complicated when dealing with high numbers of small-scale farmers and year-round demand variation from month to month. In this study, a heuristic based on a GA for multi-aquaculture, multicrop production, and polyculture for restocking and harvesting decisions (with an objective of profit maximization) is developed. Scenarios of low, medium, and high demand are set to demonstrate the mechanism of the proposed plan compared with the conventional unsynchronized restocking and harvesting method.

Keyword: Integration process planning scheduling aquaculture

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Introduction

Determining an appropriate cultivating strategy (i.e., when to raise and harvest a crop) is of great economic importance for aquaculture enterprises (Bjorndal, 1988; Yu, 2006). Scholars have long been working on the aquaculture rotation problem because solving this complex problem has become a tool for competitive business. It is a continuous operation in which harvesting decisions affect factors such as payoff, product size/growth, and the starting of new crops. To maximize the overall returns from several production cycles, the manager has to balance the returns from cycling a new crop after harvesting the current one (Bjorndal et al., 2004; Yu & Leung, 2009). In other words, the concept of multiple cycles of aquaculture is the continuous model of an aquaculture operation, which has two parts. One part is harvesting, and the other part is restocking. A new crop cannot be put in place unless the previous one has been harvested. If harvested, the pond will have to be either emptied or started with new production cycles.

Ornamental fish are no different from other aquaculture in the sense that this population is also facing complexities regarding a harvesting/culturing plan. The industry is faced with high numbers of small farmers and year-round demands vary from month to month. In response to demand variation and the finite capacity of growing out ponds, the production plan needs to be set efficiently throughout the year. Year-round fish production, harvesting, and stocking decisions are not straightforward until the previous one has been harvested. With several types of disparate information, a manager would face such a scenario by engaging multi-aquaculture, multicrop production, and polyculture, which are not easy/optimal processes. This type of problem resembles a dynamic parallel machine, product lot size case. Because it is all-in-all-out year-round production involved with multicrop production units, it is clear that the accommodation of such constraints requires the use of a suitable operational research model (Bjorndal, 2004; Sompon et al, 2017; Waraporn, 2016).

To visualize the complexity of the problem, let us explore variety of ornamental fishes with different production lead times, as shown in Figure 1. Short lead times occur with fishes such as the Betta fish and the guppy, and long lead times are indicated in species such as flowerhorn fish, gold fish and carp. Therefore, year-round continuous operations need to take the lead times of different fishes into account. To elaborate the case further, the assumption on demand variation of ornamental fish throughout the year is shown in Table 1. With long and different production lead times, not sharing information and unsynchronized harvesting decisions among farms results in supply overage and shortage. For example, if there were five farms producing gold fish and they decided to produce in full capacity and start and harvest at the same time, the fish would be oversupplied in month 5 while facing a supply shortage in months 6-10, as shown in Table 1. Conversely, if the farmers shared resources and synchronized their production plans, the supply would have been adequate for satisfying a larger portion of demand.

A variety of analytical and computational models have been proposed in an attempt to assist aqua-managers in identifying the best harvesting strategy under the general framework of optimal control/dynamic programming. While many previous models have been built to tackle the optimal harvest problem (Springborn et al., 1992; Leung et al., 1994; Hean & Cacho, 2002; Talpaz & Tsur, 1982; Cacho et al., 1991; Pascoe et al., 2002; Leung & Shang, 1989; Karp et al., 1986; Hochman et al., 1990; Spaargaren, 1999; Tian et al., 2000; Yu & Leung, 2005; Pathumnakul et al., 2007; Yu et al., 2006; Kam et al., 2008), this research has provided a theoretical foundation for a single pond or production unit (Karp et al., 1986; Guttormsen, 2008; Forsberg, 1996). We extended the aquaculture stocking and harvesting problem further to cover the year-round production planning for multi-aquaculture, multicrop production, and polyculture. This type of the production plan represents an NP-hard problem (Gray et al., 1976). Consequently, a heuristic tool is needed to practically obtain the solution. In this light, researchers have used meta-heuristic approaches to solve the production planning problem (Goren et al., 2008; Phanden et al., 2011). One of those effective tools is genetic algorithms (GAs). GAs are shown to be extremely applicable in examples of large sizes and multiple objectives. In finding the best solution to difficult problems, these algorithms imitate the biological evolution process chromosomes in the search space (Ying-Hua & Young-Chang, 2008). By applying genetic operators for selection, crossover and mutation, the reproduction of a good solution is processed iteratively until the termination criteria are reached (Goren et al., 2008).

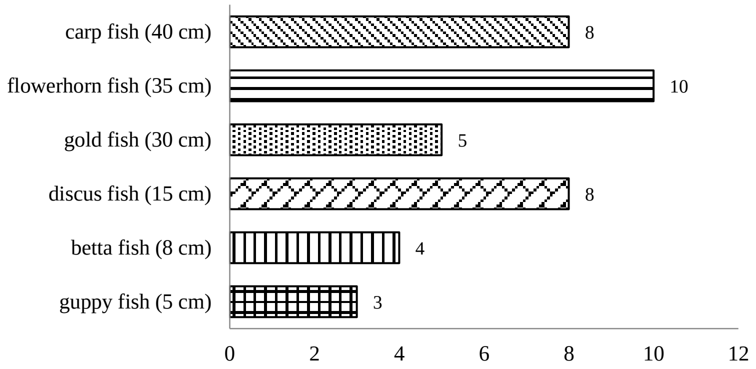

Figure 1: Production lead time of each of ornamental fish.

Table 1 Example of unsynchronized and synchronized plan of gold fish farm

Farm		Demand (5‘000 fishes)											
		5	2	3	6	5	2	1	5	7	3	6	8
		Month											
		1	2	3	4	5	6	7	8	9	10	11	12
Unsynchronized plan	1					6	0					6	0
	2					3	0					3	0
	3					4	0					4	0
	4					2	0					2	0
	5					6	0					6	0
Production (5‘000 fishes)		0	0	0	0	20	0	0	0	0		20	0
Supply shortage/overage		(-5)	(-2)	(-3)	(-6)	15	0	(-1)	(-5)	(-7)	(-3)	14	(-8)
Synchronized plan	1					5	0					6	
	2						2	0					8
	3							1	0				
	4								5	0			
	5									7	0		
Production (5‘000 fishes)		0	0	0	0	5	2	1	5	7	0	6	0
Supply shortage/overage		(-5)	(-2)	(-3)	(-6)	0	0	0	0	0	(-3)	0	0

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Objective

The objective is to maximize total profit throughout the planning horizon where farmers coordinate their production plans to satisfy year-round demand

Material and Method

In this study, a heuristic based on a GA are developed for multi-aquaculture, multicrop production, and polyculture for restocking and harvesting aquaculture. The model is developed to derive harvesting and restocking times for a predefined planning horizon (i.e., temporal duration) that maximizes total profit for multi-aquaculture, multicrop production, and polyculture for ornamental fish farm. The objective is to maximize profit of the fish production while ensures that 1) the total number of ponds being operated will not be greater than the demand of the market. 2) the amount of fish stocked in each production cycle does not exceed the stocking density of the ponds. 3) each pond can culture one fish species at a time. 4) the continuity of the fish production is maintained. 4) the new production will not start before the completion of the setup process. 5) quantity of fish quantity is a non-negativity. Details of the model are explained next.

Genetic Algorithms

The overall procedure of the proposed approach or GA for the aquaculture production planning is described as follows:

Step 1: Initialization Process

Chromosome encoding and decoding

Step 1.1: Chromosome Encoding

A population of chromosomes is initiated in this step. As shown in Figure 2, a chromosome or a production plan consists of segments (*s*, planning periods), parts (*a*, number of grow-out pond in each period), and genes, which contain fish quantity (q_{fp}), fish type (*f*) and pond (*p*). It should be noted that number of parts (grow-out pond) may vary depending on demand.

Step 1.2: Chromosome decoding

The decoding process transforms segments, parts, and genes into a cultivation plan by adding production lead time to each gene of the chromosome as shown in Figure 2

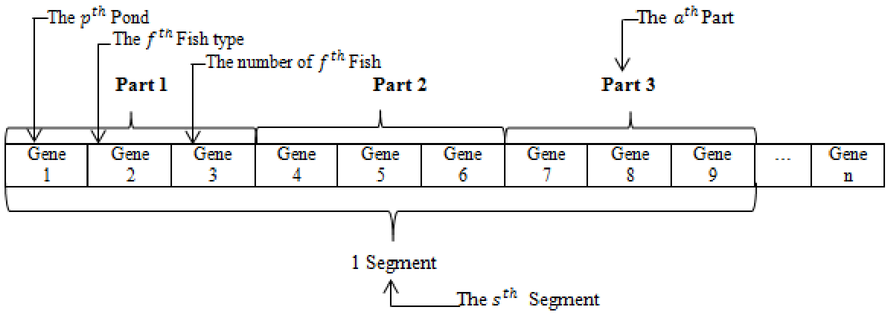

Figure 2: A chromosome structure

Step 2: Evaluation

The feasibility of the plan constraining in a chromosome is evaluated by checking 3 attributes: 1) The demand satisfaction. 2) The production capacity of the pond. 3) Feasibility of the schedule according to the constraints in the mathematical model. If the 3 criteria are met, the profit of the plan is obtained then go to step 3; otherwise, go to step 1 to recreate the population up to a specified population size.

Step 3: Selection

The procedure is a random selection of parent chromosomes to reproduce the offspring. The probability (*P*) of each chromosome to be selected is calculated as the proportion of its fitness function (profit of each chromosome in this case) to the sum of the fitness function of all chromosomes in the current generation. Hence, the higher the fitness function (profit) is, the higher is the probability of a chromosome to be chosen as a parent chromosome. For the choice of parents, the roulette wheel method is used. A roulette wheel circle is a divided sector where the number of the sectors is the number of chromosomes in the population pool. The chromosomes are ranked from the highest to the lowest probability (Table 2 shows an example of chromosome ranking). After each rotation of the wheel, a random number is generated within [0,1], the chromosome is chosen according to the generated number.

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Table 2 Probability assignment

Chromosome	Fitness function = Profit	Probability	Cumulative Probability
C-1	391,000	0.4	0.4
C-2	280,000	0.3	0.7
C-3	230,000	0.2	0.9
C-4	158,000	0.1	1
Total	1,059,000	1.0	

Step 4: Crossover

After the parent chromosome is selected, the next process is to determine the position of the crossover point and generate a cut point. As shown in Figure 3, the cut point can be at either the beginning or the end of the part. The chromosome is swapped at the cut point. This process yields 2 offspring chromosomes. The parameter P_c denotes the crossover rate being assigned to a possible cut point. It is recommended that $P_c \geq 0.9$.

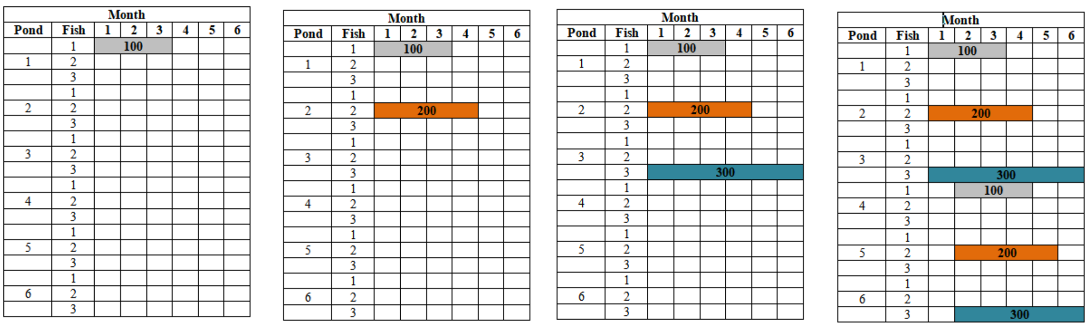


Fig. (a) Decoding for Chromosome 1 Segment 1 Part 1

Fig. (b) Decoding for Chromosome 1 Segment 1 Part 1

Fig. (c) Decoding for Chromosome 1 Segment 1 Part 1

Fig. (d) Decoding for result Chromosome 1

Figure 3: Chromosome decoding

Step 5: Mutation

The previous crossover operator swaps the whole chromosome at the cut point of the two parents. Mutation, as shown in Figure 4, is the step where only a selected gene is swapped. Any genes in any position of the chromosome can be candidates. It is recommended to use $P_m \geq 0.1$. The mutation gives new chromosomes which are subject to a reevaluation process (step 2-5) in order to select the best chromosome for step 6.

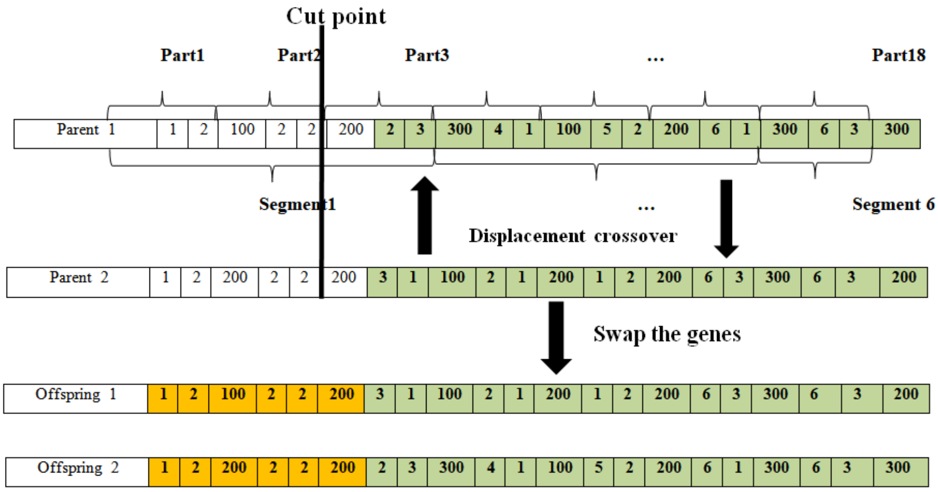


Figure 4: Crossover procedure

Step 6: Termination Test

The algorithm stops when the objective function attains a specific value, or when the maximum number of generations is reached, or a given number of generations do not improve the fitness function.

Iterations of 50,000 and 100,000 rounds are tested, and it is found that there is no obvious improvement when the number of iterations exceed 50,000. The solutions seem to converge after the first 50,000 rounds. Hence, 50,000 iterations are used. The population size is 200.

Comparison between solutions of the GA and the mathematical model

In this section, the data used to generate test problems are three sets of demands. Profits from selling each fish type and the maximum capacity of each pond are shown in Tables 3-5.

Table 3 Three generated demand sets

Month	Low Demand Set 1 1,000-5,000 fish/month			Medium Demand Set 2 6,000-20,000 fish/month			High Demand Set 3 30,000-60,000 fish/month		
	Fish 1	Fish 2	Fish 3	Fish 1	Fish 2	Fish 3	Fish 1	Fish 2	Fish 3

1	1,500	3,000	1,000	15,000	8,000	6,000	30,000	30,000	30,000
2	2,000	2,000	1,000	18,000	8,000	7,000	30,000	30,000	30,000
3	2,500	2,500	1,500	16,000	9,000	8,000	40,000	30,000	30,000
4	3,000	2,000	1,500	17,000	12,000	9,000	40,000	35,000	30,000
5	3,500	1,500	2,000	18,000	12,000	10,000	50,000	35,000	40,000
6	2,000	2,000	2,000	15,000	13,000	7,000	50,000	35,000	40,000
7	4,000	3,000	2,000	16,000	9,000	8,000	60,000	40,000	35,000
8	5,000	2,000	1,500	18,000	9,000	9,000	60,000	45,000	35,000
9	4000	4,000	1,500	19,000	10,000	8,000	50,000	40,000	35,000
10	3,000	2,000	1,500	17,000	10,000	6,000	60,000	40,000	40,000
11	3,500	3,000	2,000	15,000	12,000	11,000	40,000	45,000	40,000
12	4,000	2,000	2,500	17,000	15,000	12,000	40,000	45,000	35,000

Note: Demand data are randomly uniform distribution u [x, y]

Table 4 Setup time, profit, loss sale penalty cost, holding cost, length of cultivation

	Setup time	Profit	Lost sale penalty cost	Discount price	Length of cultivation
Fish type	Month	US Dollar/fish type	US Dollar/fish type	US Dollar/fish type	Month
0	-1	-	-	-	-
1	1	0.56	0.14	0.02	3
2	1	1.42	0.28	0.14	4
3	1	5.69	1.42	0.28	6

Table 5 Pond capacity for each fish type

Pond	Fish type	Capacity	Pond	Fish type	Capacity	Pond	Fish type	Capacity
	1	3,000		1	3,000		1	3,000

1	2	2,000	11	2	2,000	21	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
2	2	2,000	12	2	2,000	22	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
3	2	2,000	13	2	2,000	23	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
4	2	2,000	14	2	2,000	24	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
5	2	2,000	15	2	2,000	25	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
6	2	2,000	16	2	2,000	26	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
7	2	2,000	17	2	2,000	27	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
8	2	2,000	18	2	2,000	28	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
9	2	2,000	19	2	2,000	29	2	2,000
	3	1,000		3	1,000		3	1,000
	1	3,000		1	3,000		1	3,000
10	2	2,000	20	2	2,000	30	2	2,000
	3	1,000		3	1,000		3	1,000

Comparison of the unsynchronized plan and the proposed model

Without collaborative planning, each farmer cultivated fish with full production capacity using an ALL-IN-ALL-OUT process. This often causes supply overage and shortage, as indicated earlier. The excessive production is subject to be sold at a discount price and stock out is subject to lost-sales. Assuming that excessive fish is sold at a price of α_f per fish and the lost sales is penalized at a cost of δ_f per fish. Table 6 shows these numbers for all fish species.

Table 6 Comparison of the solutions and computational time between GA and LINGO

Case	Ponds	Planning horizon (Month)	(a) LINGO (US Dollar)	(b) GA (USD)			% difference of (a) and (b)	(c) LINGO (minutes)	(d) GA (minutes)			% difference of (c) and (d)
				Best	Mean	SD			Best	Mean	SD	
1	5	3	543.8	526.6	521.4	5.53	3.16	5	1	0.27	0.	80.00
		6	1187.	1116.	1087.	35.20	6.02	7	1.3	1.05	0.	81.43
		12	5581.	5180.	5169.	50.95	7.18	13.55	2.5	2.42	0.	81.55
2	10	3	1087.	1030.	988.0	97.98	5.26	9.55	1.5	1.11	0.	84.29
		6	3420.	3119.	2723.	179.3	8.79	14.05	2.15	2.08	0.	84.70
		12	8844.	7985.	7616.	262.9	9.71	23.33	4.03	3.98	0.	82.73
3	15	3	1743.	1571.	1488.	123.9	9.85	13.53	2.16	2.1	0.	84.04
		6		8443.	7310.	756.5	10.33	23.55	5.2	5.1	0.	77.92
		12	2000	1774	1640	952.1	11.30	35.15	7	6.8	0.	80.09
4	20	3	2747.	2490.	2444.	109.9	9.38	25	6.3	5.05	0.	74.80
		6	1685	1476	1395	191.3	12.39	27.07	7.39	7.12	0.	72.70
		12	2630	2347	2294		10.77	37	10.1	10.1	0.	72.62
5	30	3	4350.	3835.	3616.	114.2	11.84	46	8.5	8.21	0.	81.52
		6	2475	2146	2061	256.7	13.29	55	12.1	12.0	0.	77.91
		12	3786	3148	2714	1681.	16.86	60.25	15.0	14.9	0.	75.02
	Aver						**9.67**					**79.42**

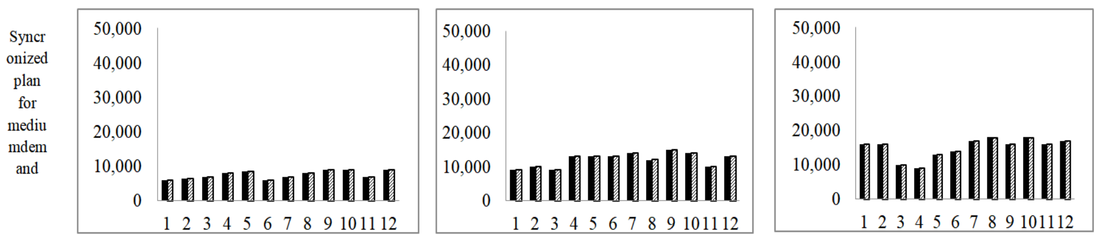
To compare the unsynchronized plan and the plan generated from the proposed model, scenarios of low, medium and high demand of fish per month are created and drawn from uniform distribution with the following parameters: Low demand ~U(1,000,5,000) Medium demand ~U(6,000,20,000) and High demand ~U(30,000, 60,000). There are 30 ponds in the test cases and the planning periods are 6 and 12 months. Table 6 shows solutions from GA and that the unsynchronized plan differs by 29.95 percent on average show that Table 7.

Table 7 Comparison of response improvement when comparing between the traditional method and GA

Case	Planning horizon	Traditional Method(USD)	GA (USD) (b)	% difference

	(Month)	(a)	Best	Mean	SD	of (a) and (b)
Low demand	6	17459.48	21466.57	20615.35	256.79	22.95
	12	25273.31	31484.31	27147.20	1681.40	24.58
Medium demand	6	22310.92	28307.25	277046.15	279.52	26.88
	12	41502.04	53380.21	48055.07	2115.16	28.62
High demand	6	28264.32	38639.83	35105.00	311.72	36.71
	12	48511.59	66858.36	62354.67	2798.37	37.82
Average						**29.95**

In Figure 5, for the low demand case, the unsynchronized plan causes the production of all fish to exceed the demand. While the proposed planning framework suggests cultivating all 3 types of fish to satisfy demand, which is less than the capacity of the ponds. For average demand about 6,000 – 20,000 fishes per month. The unsynchronized plan still causes the production of all fish types to exceed demand. This situation again represents a supply overage case which results from an uncoordinated plan. Similar to the low demand case, the proposed planning suggests producing less than the capacity of the ponds with production higher than the low demand case. For the high demand case (30,000 – 20,000 fish/month). The unsynchronized approach results in the production of some fish types over the demand and vice versa in other cases. This situation represents a mixture of supply shortage and overage. While GA allocates production capacity to fish, which yields the highest profit among the three, fish 2 and 3, and none for fish 1, which has lowest profit among all fishes.



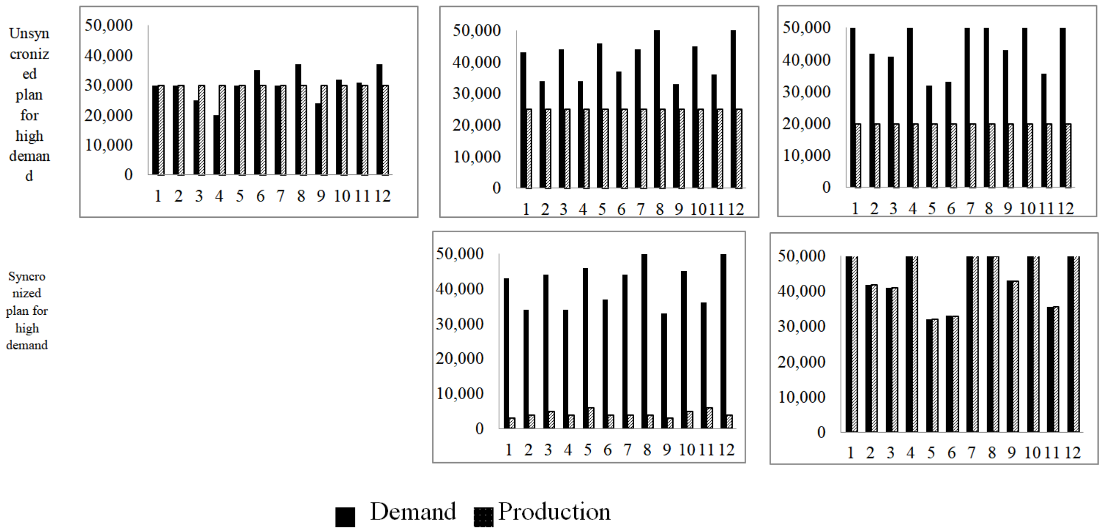


Figure 5: Unsynchronized vs. synchronized production plan for low, medium, and high demand scenarios

Conclusions

In response to the demand difference and the limited capacity of growing out ponds, it is necessary to set the cultivation plan efficiently to balance the supply and demand of fishes throughout the year. Such a decision, although common for managers, involves in several types of disparate information which is still not optimally processed. In this study, production planning resembles multi-aquaculture, multicrop production, and polyculture is investigated.

The proposed genetic algorithm (GA) is compared to contemporary practices to elaborate the benefit of synchronization. With the scenario analysis, this study also demonstrated the application of the framework through a test problem of 30 ponds and 3 fish species. The results from the genetic algorithm presented different restocking and harvesting times for each species of fish in specific ponds and were predictively scheduled across several scenarios to maximize the overall returns. The significant benefit intensified the importance of having a synchronized plan. Although the demonstration is based on the simulated datasets, the suggested framework is very practical, and it can be adapted for considering an actual issue. This framework has the potential to facilitate farmers' coordination of their production plans.

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