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Optimizing salmon farm cage net management using integer programming

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Salmon farming in Chile constitutes one of the nation's principal food exporting sectors. In the seawater stage, one of the most important in the farm production chain, salmon are cultivated in floating cages fitted with nets that hold the fish during the entire grow-out process. The maintenance of the cage nets is carried out at land-based facilities. This article reports on the creation of an integer programming tool for grow-out centres that optimizes resource use, improves planning and generates economic evaluations for supporting analysis and decision-making relating to the maintenance, repair and periodic changing of cage nets. The tool prototype was tested in a single operating area of one of Chile's largest salmon farmers. The results demonstrated a reduction in net maintenance costs of almost 18%, plus a series of important qualitative benefits. Implementation of the tool by farm operators awaits the end of the current crisis in the industry.

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1. Introduction

The introduction of exotic marine species in Chile took place primarily between 1850 and 1920. Salmon, however, were not brought to the South American nation until 1921. The first salmon farming operations in the country appeared in the early 1980s, and by 1985 there were 36 Chilean farm centres producing a total of about 1200 tonnes of salmon annually. The following year, with a significant expansion already underway as production surpassed 2100 tonnes, operators joined forces to consolidate the industry by forming the Asociación de Productores de Salmón y Trucha de Chile, the sector's first trade association known today as SalmonChile.

In 1990, operators initiated local development of reproduction activities with the cultivation of the first Coho salmon eggs, now one of three types that are produced (the other two being trout and Atlantic salmon). This milestone is considered the first scientific advance in the area by Chilean fish farmers and marked the beginning of a trend toward more technologically sophisticated methods. Most of the major improvements in salmon feeds have also come about since that time. The rise in output volumes has brought with it the professionalization of the industry and the incorporation of dry feeds with increasing content in lipids and a more efficient balance between them and proteins.

Yet despite the progress of the industry and its markets, Chilean salmon farmers found themselves facing a major challenge in 1998 as the outbreak of the Asian financial crisis led to falling prices for Japan-bound exports and overproduction around the world. Fortunately, by taking appropriate measures local operators were able to surmount the difficulties and continue increasing their output.

By 2008, salmon farming was already Chile's fourth largest export industry, directly or indirectly employing more than 45 000 people. The country had become the world's number two producer of salmon with annual sales of more than 2.3 billion dollars, a figure bested only by Norway. That same year, however, a new crisis erupted as the ISA virus spread rapidly through the majority of seawater farming centres, dealing a serious blow to the sector's development (Godoy *et al*, 2007). Chilean production dropped from a record high of 620 000 tonnes in 2008 to 460 000 in 2009, 450 000 in 2010, and 410 000 in 2011. Employment in the industry was also hit, falling to about 25 000 workers as of early 2011. Nevertheless, Chile continues to be the second largest producer and output in 2012 is expected to return to 2008 levels.

According to many experts, the impact of the virus demonstrated how Chile's salmon farmers, unlike the

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major Norwegian producers, failed to take advantage of the sector's rapid growth over the decade preceding the crisis to implement a vigorous modernization of their operating logistics. This weakness points up the need for developing advanced tools, such as the one presented in this article, to update the industry's management techniques. It should also be noted that although the increases in international demand and average prices, the latter rising from 3 dollars per kilo of salmon in 2001 to almost 7 in 2011, have been very beneficial, both of these factors are exogenous variables for Chilean operators. If they are to deal effectively with future fluctuations it is therefore all the more essential that their logistics and productive processes generally be organized efficiently.

The prototype optimization tool reported here was created for a pilot project implemented in 2008 at Salmones Multiexport, a salmon farmer owned by Multiexport Foods and one of the industry's major players both in Chile and internationally. Founded in 1989, the operator is active in the production, processing and marketing of salmon and trout raised in the country. It maintains hatcheries, smoltification centres, grow-out sites and processing plants in the 9th, 10th and 11th Regions of southern Chile. The company is vertically integrated, engaging in every stage from reproduction to distribution and sales. The cultivation of salmon can be divided into three stages:

1. *Reproduction*: the production of salmon eggs at specialized reproduction and genetics centres (1–2 months).
2. *Freshwater rearing*: the cultivation of the fish in freshwater tanks kept in large hangars until they reach the appropriate weight for transfer to centres located at rivers or lakes where they adapt to salt water conditions, a process known as smoltification (10–14 months).
3. *Seawater grow-out*: the longest stage, in which the fish are fattened at marine centres where they remain until ready for relocation to the production phase (16–20 months).

In this last stage the salmon are developed in floating net cages suspended from rafts where the fish are held during the entire grow-out process.

The purpose of the pilot project was to build an operational research tool that would optimize resource use, improve planning and generate economic evaluations which would enhance analysis and decision-making related to the maintenance, repair and periodic changing of salmon farm cage nets.

For many years the development of optimization models has paralleled the evolution of high-volume salmon farming methods. Various authors have investigated these mathematical techniques in the search for greater growth and productivity (Brown and Hussen, 1974; Hilborn, 1989; Hilborn and Walters, 1992; Rye and Mao, 1998; Crampton *et al*, 2003; Pomeroy *et al*, 2008) or improvements in farm operation planning (Gustavson, 1972; Rothschild, 1986; Forsberg, 1996; Forsberg, 1999; Jensson and Gunn, 2001; Yu and Leung, 2006). Their efforts have done much to demonstrate the positive impacts and benefits of such approaches and the real need for the application of optimization models in the industry. Other research at a more general level has underlined the importance of employing quantitative methods in fisheries and aquaculture (see Bjørndal *et al*, 2004 and Weintraub *et al*, 2010).

A number of studies have focussed on improving the social welfare generated by the European salmon farming sector, and particularly that of Norway (Asheim *et al*, 2005; Färe *et al*, 2009). Currently the world's largest, its structure differs greatly from the Chilean industry in that Norwegian producers, though greater in number, tend to be smaller in size and typically do not integrate the whole production chain.

There is also a literature on the optimization of salmon feeding, which plays a significant role in both production costs and final product quality (Forsberg and Guttormsen, 2006; Stien *et al*, 2007). Yet another important factor that has been addressed in recent years is the pollution generated by the industry. Buyers today are concerned not only about the quality of the salmon but also about how they are raised, and this reality has prompted researchers to look into issues of feed type and contamination in salmon production (Leung, 2005; Liu and Sumaila, 2010).

In Chile only certain results of European research have been adopted by the country's salmon farming sector. Owing to its particular characteristics, local implementation of these advances has necessarily been indirect and undertaken only where case-by-case analysis confirms their applicability. But often even this is not sufficient to ensure the solutions developed will resolve problems peculiar to the Chilean context, and with this in mind the present work will, it is hoped, pave the way for further research aimed more specifically at the circumstances facing local operators.

‘To the best of our knowledge, the mathematical optimization tool we propose for scheduling the maintenance, repair and periodic changing of salmon farm cage nets is the first of its kind in the literature. In addition, both the empirical results delivered by the tool for one of the main operating areas of the firm where it was implemented (Section 4.1) and the various sensitivity analyses that were carried out (Section 4.2) constitute, we believe, a worthwhile contribution to the literature on salmon farm logistics.

The remainder of this article is structured as follows. Section 2 describes the particular problem that will be addressed, Section 3 introduces the mathematical model that was developed into the optimization tool, Section 4 sets out the results obtained and the tool's impacts, and Section 5 presents our conclusions.

2. Description of the problem

2.1. Characteristics of fish farm cage nets

Fish farm cage nets are made with various types of nylon or polyester to ensure high flexibility for easy handling and transport.

The most common cage net dimensions are 30 metres long by 30 metres wide and 20 metres long by 20 metres wide, with depths varying from 10 to 17 metres (see Figure 1). The magnitude of the net openings varies depending on the size of the salmon kept in the cage. For fish weighing less than 1 kg, the openings measure 1 inch while for larger fish, a 2-inch mesh is used.

In addition to cage nets, a stronger type of net is employed to protect the cages against predators such as sea lions.

2.2. Net maintenance

Over time, the nylon or polyester nets are subject to deterioration and/or fouling by organic matter adhering to the mesh due to its exposure to seawater. They must therefore be periodically changed and sent for maintenance.

Net maintenance consists of three main stages carried out at maintenance facilities run by specialist companies. The stages are:

Cleaning: Nets are taken to a maintenance facility where they are cleaned to remove the fouling matter. This is done in drum-type washing machines known as hydrowashers or with high pressure hoses. The nets are then disinfected in compliance with biosafety regulations.

Repair: After cleaning and disinfection the nets are inspected by teams of three persons who check them thoroughly for tears or other damage and make any necessary repairs. They are then sent for antifouling treatment or to a storage site for pickup by the owners.

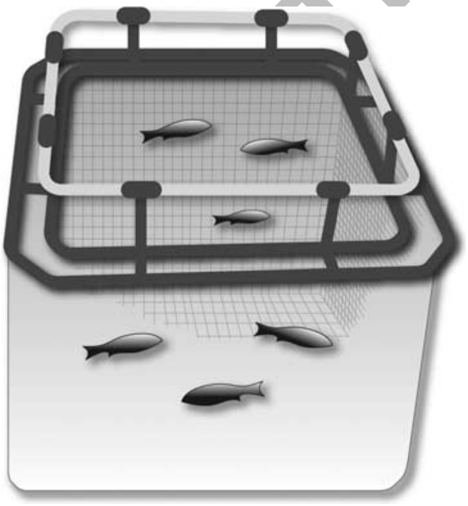

Figure 1 Cage net.

Antifouling: Treating with antifoulant involves an additional cost but extends the in-water life of the nets.

2.3. Net deterioration factors

The principal causes of deterioration of nets in the water are the following:

Algae growth: The growth of algae and other fouling adhering to the nets weakens them and increases their weight, rendering them more difficult to handle and increasing the risk of tearing. Fouling also has a negative impact on fish development given that a 'dirty' net reduces water circulation and therefore water oxygen levels. This makes the fish lethargic and lowers their food intake, leading to increased mortality. Since algae growth is directly related to sunlight, these effects are exacerbated in the summer.

Sea lion attacks: Sea lions, a protected species in Chile, are one of salmon's natural predators. These marine mammals are capable of breaking the netting to get at the fish, causing major losses for farm operators. As noted above, a stronger mesh known as a sea lion net is placed over the cages to protect against such attacks (unless otherwise indicated or implied by context, references to nets hereafter are to cage nets, not sea lion nets).

Environmental conditions: Cage nets are not subject to major deterioration due to the weather, but in particularly extreme conditions wear and tear does increase.

2.4. Economic losses due to deterioration factors

Deterioration factors that are not promptly addressed may lead to a number of problems:

Net rupture: The rupture of a net can result in a major escape of fish, with the consequent damage to a farming centre's investment. Based on the experience of operators like Multiexport, a torn mesh resulting in the loss of about 10% of cage contents occurs, on average, once every 2 or 3 years. Assuming that a typical cage contains approximately 90 000 salmon with a mean weight of 3 kg, the cost to the firm of such an escape would amount to about 200 000 dollars.

Growth problems: The reduction in oxygen levels due to algae growth slows fish development, thus prolonging grow-out time. This in turn lengthens the investment recovery period, increasing salmon cost per unit weight produced while decreasing site availability for subsequent harvests.

2.5. Preventive measures

Preventive measures include the following:

Periodic net inspections: Net inspections include checks by divers of algae growth and the general state of the nets, plus laboratory testing of net samples for fibre strength and tension.

Regular net maintenance: Regular net maintenance involves various stages and actors. It begins with the visit to a farming centre of a dedicated net boat to change any nets found to be torn or dirty. After replacing them with clean ones in good condition, the removed nets are transported by the same boat to the closest convenient port where they are then transferred to a truck and driven to a net maintenance facility for cleaning and repair. The net owner may also decide to have them treated during this stage with antifoulant to reduce algae adhesion.

2.6. Costs and decision-making

The preventive measures just described are essential to the correct use of cage nets but involve major costs for the farm operators. For a firm like Multiexport, expenditures on net inspection and maintenance add up to about 10 million dollars a year. This includes net facility maintenance, antifouling treatment, new net purchases, net boat rental and diver hire, and marine fuel and truck rental for net transport to the nearest port and on to the facility.

Operators must therefore make a series of important decisions regarding net acquisition and care. These include when to remove a net and change it for a clean one, when to replace a net with a bigger one (due to growth in fish size), whether a net sent for repair should be treated with antifoulant, how many nets to buy and when to buy them, which centres the net boats should visit in a given week, and when the sea lion (predator) nets should be changed.

Beyond the obvious considerations of net boat availability and maintenance facility capacity, firms in the industry currently make these decisions purely on the basis of expert judgement unaided by any specific support tools.

The net maintenance problem is strongly impacted by external conditions such as sunlight levels, which increase net fouling, and climatic conditions, which can delay or prevent net boat operations. Inadequate planning of maintenance facility visits can also negatively affect response times.

Once the quantity of installed nets reaches significantly large numbers (Multiexport had approximately 800 nets installed when the pilot project was implemented) and the associated maintenance requirements are sufficiently varied, monthly maintenance planning can become difficult to manage. Drawing up semi-annual or annual projections using manual methods takes several days, resulting in considerable loss of expert person-hours with little hope of identifying efficient solutions. Analysing all the possible combinations in order to make judicious decisions with no technological support other than Excel log sheets is well-nigh impossible. Clearly, the availability of a mathematical programming tool that supported the decision process once operations reached a certain scale would be highly advantageous.

3. Integer programming model

The problem described in the previous section was modelled using integer programming (IP). In this section we outline certain conceptual aspects of the model before introducing its mathematical formulation.

3.1. Conceptual description of the model

Salmones Multiexport operates over a long stretch of coastline in southern Chile which has been divided for convenience into several geographical operating areas. A single area has 4-6 centres that share rented net boats and the services of one third-party net maintenance facility. Every centre has two modules, each of which contains 14 cages. The cage is thus the basic salmon rearing unit and is fitted with a net that holds the fish in periods when it is active. Since each operating area's net maintenance and transport operations function independently, the problem for each area can be solved individually. Note also that our model is concerned only with cage nets; decisions regarding the sea lion nets are determined separately.

Before describing the actual IP model, we set out the model's inputs:

- The *model time horizon* expressed in weeks. The authors recommended using time units of one week as this period gives the model both flexibility and operability. The suggestion was well received by the company's planning team and was therefore adopted.
- The *types of net* used in the operating area and their *basic characteristics*:

    - The size of the net, in m^2.
    - The weight of the net, in kg.
    - The initial stock.

- The number of *centres* in the operating area and their *basic characteristics*:

    - The number of cages in each centre.
    - The distance to the nearest port, in km.

- The *number of available net boats* and their characteristics and related factors:

    - Daily capacity, that is, the activities they can carry out in a single day. (Net boat divers remove nets to be sent for maintenance and install new or repaired ones. The two tasks together make up a complete *net change* and are considered as separate activities that

  can be conducted on different days, but only in the order indicated.)
  - Number of operating days, defined separately for each week. Though typically this value will be five, it can be set or modified to incorporate any relevant factor. Typical examples would be the days devoted exclusively to sea lion net change or eventualities affecting continuity of transport services such as net boat mechanical problems, labour disputes or legal holidays. The weekly values chosen may also allow for port closures due to climate variability issues. Optimization for climate variability in other natural resource contexts has been analysed in previous studies in the literature (see Letson *et al* (2005) and Cabrera *et al* (2006)).
  - Fuel consumption and marine fuel prices (which are combined with data on sailing distances to the nearest port to calculate each centre's transport cost). We assume that for bio-security reasons, net boats sail directly to the ports and back without calling at any other centres.
  - The centres each boat may sail to.
    Note that since Multiexport contracts annually for a set number of net boats as determined by company experts, the number of boats in the model is fixed. In Section 4.2.1 we study the impact of small variations in this parameter.

- The maximum continuous time a net may be kept in the water, in weeks (hereafter also called *net in-water time limit*). This parameter is specified in the system as a function of whether or not the net has been treated with antifoulant and the season it was installed in. An untreated net installed in the summer must not remain in the water more than 4 weeks while in winter it may be left in up to 8 weeks. A treated net may stay in the water up to 12 weeks in summer and 16 weeks in winter. In Section 4.2.3 we study the impact of small variations in these parameters.
- The net maintenance *facility response time*, in weeks (including actual maintenance time and transport time from the centre to the facility and back). In Section 4.2.2 we study the impact of small variations in this parameter.
- The *net maintenance cost* charged by facilities, in (US\$/m^2).
- The *antifouling treatment cost* charged by facilities, in (US\$/kg).
- The *net demand* for each cage in each week. The type of net required for each cage in each week is specified using company-supplied data on centre operations (production plans, Gantt chart, etc).
- The currently installed nets, their in-water times and net types for each cage at the beginning of the planning horizon. This parameter gives the history of each cage.

The definitions of the set of constraints that model the fundamental aspects of the optimization problem are based on the above-described input data. Net demand must be satisfied for each cage in each week within the planning horizon. Additional constraints are defined to ensure observance of the weekly limits on net boat activity imposed by their respective capacities. Subject to these restrictions and conditions, the model minimizes total costs for the maintenance, antifouling treatment, water transport and purchase of cage nets.

In addition to delivering the required data for establishing a net maintenance plan, the model indicates the number of trips to each centre, the number of nets in use (installed in cages or in maintenance) in each period and the number needed for the entire horizon (the critical net stock) including how many must be purchased.

The sea lion nets must also be changed periodically, though not as frequently as the cage nets. After discussions with the operator it was decided that the dates of the sea lion net changes would be determined exogenously to the model by company personnel. This factor is nevertheless incorporated in the model by varying the number of working days parameter as required for each week in the time horizon to free up the necessary resources for carrying out the changes. The model thus offers total flexibility in scheduling individual days or entire weeks for this activity. The two schedule alternatives implemented in the scenario analysed here were one week in every four and one day each 5-day week, held constant in each case for the entire 24-week horizon. Preliminary tests show that the two options yield similar results (see Section 4.2.4).

Road transport of nets between the ports and the maintenance facilities in either direction is not incorporated in the model because the company pays a fixed annual cost for truck rental, which in any case is much lower than the cost of sea transport between the farm centres and the ports.

The parameter values (net boat activity capacities, number of net boats, number of centres, response time, etc) will vary depending on which operating area is being planned, and can be modified in the model without changing its structure.

Given that new nets are readily available commercially, maintaining a stock to cover demand uncertainties is unnecessary.

3.2. Mathematical formulation of the model

We now state the IP model as follows (model indices, parameters and decision variables can be found in Tables 1–3):

$$\text{minimize} \sum_{kjtdp} (MAIN_k + PAINT_{kp}) \cdot X_{kjtdp} + \sum_{k} PUR_k \cdot PN_k + \sum_{bct} TRN_c \cdot W_{bct} \qquad (1)$$

Table 1 Sets of indices used with model parameters and variables

Indices	*Description*
$t \in \{0, \ldots, T\}$	The set of periods, where T is the total number of one-week periods in the planning horizon. Period 0 represents the beginning of the horizon; the decisions for this period affect the already installed nets.
$k \in \{1, \ldots, K\}$	The set of net types, where K is the total number of net types in use.
$j \in \{1, \ldots, J\}$	The set of cages, where J is the total number of cages in all of the centres.
$c \in \{1, \ldots, C\}$	The set of active centres, where C is the total number of centres.
$J_c \subseteq \{1, \ldots, J\}$	The set of cages belonging to centre $c \in \{1, \ldots, C\}$.
$p \in \{0, 1\}$	The antifouling treatment state p of a net to be installed, where $p = 1$ indicates that it has been treated and $p = 0$ that it has not.
$b \in \{i, \ldots, B\}$	The set of net boats, where B is the total number of boats.

Table 2 Model parameters

	Parameter	*Type*	*Description*
1	DEM_{kjt}	$\{0,1\}$	Indicates whether or not a type k net is demanded for cage j in period t.
2	$NIWT_{ktp}$	$\mathbb{Z}_+$	In-water time limit of type k net installed in period t with antifoulant in state p.
3	REP	$\mathbb{Z}_+$	Net repair time, counted from the moment a net is removed from its cage.
4	TRN_c	$\mathbb{R}_+$	Transport cost for a single round trip from port to centre c and back (incurred when one or more nets are installed and/or removed at centre c).
5	PUR_k	$\mathbb{R}_+$	Purchase cost of a type k net.
6	$MAIN_k$	$\mathbb{R}_+$	Maintenance cost of a type k net.
7	$PAINT_{kp}$	$\mathbb{R}_+$	Antifouling treatment cost of a type k net in antifoulant state p ($\mathrm{PAINT}_{k0} = 0$).
8	$HIST_{kjp}$	$\mathbb{Z}_+$	Number of periods a type k net has been installed in cage j with antifoulant in state p, at the beginning of the planning horizon.
9	$HAUX_{kjp}$	$\{0,1\}$	Indicates whether or not cage j has a type k net with antifoulant in state p in period 0 (ie, $HAUX_{kjp} = 1$ iff $HIST_{kjp} > 0$).
10	STO_k	$\mathbb{Z}_+$	Initial stock of type k nets.
11	BC_{bc}	$\{0,1\}$	Indicates whether or not boat b can visit centre c.
12	$DCAP_{bt}$	$\mathbb{Z}_+$	Daily capacity of boat b in period t (ie, maximum number of activities on one trip).
13	$DAYS_t$	$\mathbb{Z}_+$	Number of working days in week t.

Table 3 Model decision variables

	Variable	*Type*	*Description*
1	X_{kjtdp}	$\{0,1\}$	Indicates whether or not a type k net is installed in cage j in period t for the next d periods ($d > 0$), with antifoulant in state p. The X variables with $t = 0$ express decisions regarding already installed nets at the start of the horizon.
2	W_{bct}	$\mathbb{Z}_+$	Number of trips made by boat b to centre c in period t.
3	UN_{kt}	$\mathbb{Z}_+$	Number of type k nets required for period t.
4	MUN_k	$\mathbb{Z}_+$	Total number of type k nets required for the planning horizon.
5	PN_k	$\mathbb{Z}_+$	Number of type k nets that must be added to inventory to satisfy planning horizon requirements.

subject to

- Satisfication of net demand:

$$\sum_{p,\theta \in [0..T]:\theta \leqslant t, d > t-\theta} X_{kj\theta dp} \geqslant DEM_{kjt} \qquad \forall k, j, t \tag{2}$$

- The removal of previously installed nets at some point:

$$\sum_{d} X_{kj0dp} = HAUX_{kjp} \qquad \forall k, j, p \tag{3}$$

- The number of trips made by boats to centre c in period t:

$$\begin{aligned} &\sum_{k,j \in J_c, d, p} X_{kjtdp} \\ &+ \sum_{k,j \in J_c, \theta < t, \delta = t-\theta, p} X_{kj\theta\delta p} \\ &\leqslant \sum_{b} W_{bct} \cdot DCAP_{bt} \qquad \forall c, t \end{aligned} \tag{4}$$

- Limit on the overall number of activities made by boats to all centres in period t:

$$\sum_{c}\left[\sum_{k,j\in J_c,d,p} X_{kjtdp}+\sum_{k,j\in J_c,\theta<t,\delta=t-\theta,p} X_{kj\theta\delta p}\right] \leqslant \sum_{b} DCAP_{bt}\cdot DAYS_t \qquad \forall t \tag{5}$$

- Limit on the number of trips made by a boat b to a centre c in period t:

$$W_{bct}\leqslant DAYS_t \quad \forall b,c,t \tag{6}$$

- Type k nets in use in perio t:

$$\sum_{j,p,\theta\in[0..T]:\theta\leqslant t,d>t-\theta-REP} X_{kj\theta dp}=UN_{kt} \quad \forall k,t \tag{7}$$

- Maximum number of type k nets in use within the planning horizon:

$$UN_{kt}\leqslant MUN_k \quad \forall k,t \tag{8}$$

- Number of nets that must be purchased:

$$PN_k\geqslant MUN_k-STO_k \quad \forall k \tag{9}$$

- Nature of the variables:

$$X_{kjtdp} \quad \in\{0,1\} \tag{10}$$

$$W_{bct},MUN_k,UN_{kt},PN_k\in\mathbb{Z}_+ \tag{11}$$

To ensure the net in-water time limits are observed, variables X_{kjtdp} where $d>NIWT_{ktp}$ are excluded from the model. In the case of variables X_{kj0dp} those for which $d+HIST_{kjp}>NIWT_{ktp}$ are excluded, thus using the historical data for these cages to ensure the same time limit principle is applied. Also, the variable W_{bct} is included in the model if and only if $BC_{bc}=1$.

4. Results and impact

The operational research model just described forms the basis of the computational tool developed for the use of Multiexport's decision-makers. After various iterations were trialled in collaboration with company experts, a final version of the application was settled on that proved to be both practical and easy to use, requiring no knowledge either of programming or optimization.

The tool can generate net maintenance schedules for a given horizon for each of the company's geographical areas. Once the necessary historical net data have been inputted, the application can also produce reports on the maintenance process, calculate the associated costs and compare them with previous scenarios. In the spirit of adapting the software to established Multiexport procedures rather than the other way around, the maintenance order formats generated by the tool reproduce those of the company's existing forms.

To evaluate the model's performance we compared its solutions with those produced by company planners using their traditional manual scheduling methods. The scenario used for the evaluations was a 24-week horizon during the first half of 2008 in Dalcahue, one of the operator's largest operating areas accounting for some 20% of the company's entire seawater grow-out capacity.

The application was developed in C++ and generates an OPL 1.71 model that is solved with CPLEX 11.2 running on a 2.00 Intel RCoreTMDuo T7200 processor with 1 GB of RAM. To represent the prevailing situation in Dalcahue, the IP model incorporated approximately 32 000 variables and 2100 constraints. Run times for the scenario were about 2 min, with an optimality gap threshold of 0.5%. The model sizes and run times were similar for the preliminary tests conducted on the company's other operating areas.

4.1. Evaluation of Dalcahue area

The Dalcahue operating area is located on Chiloe Island in Chile's 10th Region. It was chosen as a test bank because the local operation is a miniature version of the company's complete system, with its own stock of nets, an exclusive net maintenance facility and expert personnel with access to all the necessary data (the Dalcahue setup was to be replicated in the firm's other areas). The parameter values for the scenario analysed were the following:

- The evaluation horizon is 24 weeks (January to June 2008).
- The area has six farming centres and a total of 140 cages.
- Two net boats serve the area (both can visit any of the six centres).
- Each boat's team of divers can carry out up to seven activities in a single day. The boats operate an average of 5 days a week. Our scenario assumes that 4 days of the week are devoted to cage net changes (so that $DAYS_t=4$, for all t) and 1 day is reserved for changing sea lion nets. Thus, each boat can be used for 28 weekly net change activities over the 24-week horizon. (Recall that since a cage net change involves removing a dirty net from a cage for transport to a maintenance facility and installing a clean one in its place, the change counts as two activities.)
- Two types of cage net are used: 1-inch (1′) nets measuring 30 metres by 30 metres (1972 m^2 and 750 kg) and 2-inch (2′) nets also measuring 30 metres by 30

metres (2723 m^2 and 880 kg). The initial stock quantities are 35 and 98 nets, respectively.

- Maintenance facility response time (including transport to and from a centre) is 2 weeks.
- Untreated nets installed at the start of the horizon in summer can remain in the water up to 4 weeks; treated nets can stay in for up to 12 weeks. These values increase gradually as the time of year progresses to a maximum of 8 and 16 weeks, respectively, if the nets are installed in late autumn.

We now compare the planning results generated by the model with those produced by the company experts' manual methods for the same 24-week horizon. The experts required almost a whole day for the task and the model detected numerous infeasibilities in their first schedules, most of which were unsatisfied demands or exceeded activity limits. Without the model, these infeasibilities would not have been identified until much later in the time horizon.

The IP model generated the automatic planning results in approximately 2 min. Manually loading the scenario into the tool took about 10 min, but this process could be automated so that the input data are retrieved directly from company spreadsheets. The potential expenses incurred with both the manual and model-generated planning methods over the entire planning horizon are shown in Table 4.

As can be seen, the model reduced the total cost for maintenance, antifouling treatment, water transport and net purchases by almost 18%, corroborating company experts' intuitive belief that there was considerable potential for sizeable savings. The results also confirmed their doubts about the economic viability of treating the nets with antifoulant. The global savings indicated in the table would probably be even greater if the tool were used for day-to-day planning given that whenever an unforeseen circumstance arises, the model can simply be run again and the necessary modifications implemented, whereas manual corrections always risk creating major inefficiencies.

The computer tool also confers important qualitative benefits. In addition to solving a scenario in mere minutes, its results comply with all imposed restrictions and therefore produce no feasibility errors. Furthermore, the fast solution times allow an expert user to readily analyse an array of scenarios and identify potential investments such as additional boat rentals or maintenance facility improvement and expansion. Some of these possibilities are studied in Section 4.2.

Yet another advantage is that by virtue of the model's construction, the solutions it generates deliver a more detailed maintenance plan than the company's manual schedules, which are only approximate and in most cases projected from monthly estimates of the centres' net requirements.

An important consideration for best use of the tool in day-to-day planning is that the model should be rerun and a new planning process begun several weeks before termination of the defined time horizon. This will ensure the decisions generated are not affected by the approaching endpoint. For example, though a net may require an antifouling treatment at some moment in a perspective extending beyond the defined horizon, the model will never generate such a decision if the horizon has only a few weeks left. Rerunning the model with a relatively far off endpoint will avoid such effects caused by boundary conditions.

In order to check that boundary conditions were not distorting the savings percentages, the cost reductions generated by the model compared to the manual methods were calculated for the period up to the 12th week (50% of the time horizon) and the 16th week (67% of the time horizon). The results were a reduction of 18.86 and 17.50%, respectively, suggesting that the final figure of 17.94% for the planning horizon in its entirety is consistent with the savings achieved all through the 24-week period.

4.2. Sensitivity analysis

To identify the effects of certain variations in the original problem parameters on the model's solutions, we analysed the impacts of changes in the number of net boats, net boat capacity, maintenance facility response time, net in-water time and days devoted to sea lion net change. The findings in each case are discussed separately below.

4.2.1. Number of net boats and boat capacity. Net boats can only be contracted for relatively long periods, and rental complete with a team of divers is about US$ 500 000 per year. Since the company used two boats for

Table 4 Manual and model-generated planning results

Plan	*Expenses (in US$)*				
	Maintenance	*Antifouling*	*Transport*	*Net purchases*	*Total*
Manual	327 120	26 793	18 480	63 511	435 904
Model	305 930	18 268	15 779	17 745	357 722
Savings	21 190 (6.48%)	8525 (31.82%)	2701 (14.62%)	45 766 (72.06%)	78 182 (17.94%)

Table 5 Sensitivity analysis results for number and capacity of net boats

No of boats	*Daily activities*	*Expenses (in US$)*				
		Maintenance	*Antifouling*	*Transport*	*Net purchase*	*Total*
1	6	—	—	—	—	Infeasible
	7	—	—	—	—	Infeasible
	8	—	—	—	—	Infeasible
2	6	303 870	25 119	17 946	13 409	360 344
	7	305 930	18 260	15 779	17 745	357 722
	8	305 930	18 260	14 192	17 745	356 135
3	6	303 870	25 119	17 835	13 409	360 233
	7	305 930	18 260	15 779	17 745	357 722
	8	305 930	18 260	14 192	17 745	356 135

Table 6 Sensitivity analysis results for maintenance facility response time

Response time	*Expenses (in US$)*					*Savings (%)*
	Maintenance	*Antifouling*	*Transport*	*Net purchase*	*Total*	
1 week	313 620	0	16 739	0	330 359	7.65
2 weeks	305 930	18 268	15 779	17 745	357 722	
3 weeks	296 700	38 820	15 265	79 326	430 111	−20.24
4 weeks	288 350	69 693	14 199	154 720	526 962	−47.31

the scenario under analysis, evaluations of the same scenario assuming one and three boats were performed. Also evaluated were increases and reductions in the number of daily activities carried out by the boats, which would mean hiring more or fewer divers, respectively.

The results of the evaluations in terms of net maintenance, antifouling treatment, transport and net purchase expenses for different numbers of boats and net boat capacities (the latter expressed as daily activities per boat) are summarized in Table 5. The shaded row corresponds to the actual configuration of these parameters.

On the basis of these results, we may make the following observations:

- One boat is not enough to satisfy the scenario demand; hence at least two boats are required.
- Two boats are enough to satisfy net demand; adding a third one leaves expenses practically unchanged. Once the cost of boat rentals, not included in the table, is factored in, it is clear that a third boat should not be hired.
- Changes in the boats' daily activity capacity have little effect on total costs because of their relatively minor impact on maintenance expense, which accounts for 80% of the total.

4.2.2. Maintenance facility response time. To gauge the impact on the model solutions of net time out of the cages for repairs and/or transport, we analysed how they varied with changes in maintenance facility response time. The results are gathered in Table 6, where the shaded row corresponds to the actual configuration of this parameter.

These figures show that as response time increases, so do the required number of nets and net antifouling treatments to satisfy the needs of the operating area. Despite the fact that maintenance and transport expenses decrease, overall costs rise very significantly due to the increase in the response time parameter. Close management is therefore recommended for two key aspects related to response times. The first is compliance with maintenance facility repair times and the second is compliance with transport times to and from the farm centres (including dead time). Any delay in either of these factors will change the strategy generated by the model and its associated costs. Since response times are highly sensitive to net maintenance time at the repair facility, operators should tighten control of deadline compliance and give the facilities advance notice of net maintenance schedules. This would allow them to plan ahead and better ensure response times are met. A graphical depiction of the cost variations is given in Figure 2.

Note in conclusion that if the company were able to reduce response time to one week, the model solutions could achieve savings of about 7%. Of course, this would require investing in improved maintenance facilities. The percentage savings give some idea of how much investment or additional expenditure on net maintenance would be worth undertaking to generate the benefits.

4.2.3. Net in-water time. To understand how the model solutions varied with changes in the net in-water time limits for both treated and untreated nets, we analysed several scenarios in which the limits were increased or decreased. The results are shown in Table 7, where '+ 2 weeks', for example, indicates that all of the limits are extended by two weeks.

As can be seen, a relatively cautious or conservative net change criterion requiring more frequent changes generates higher costs than a more optimistic rule allowing the nets to be left in the water longer. Indeed, small increases in these parameters appear to generate significant savings, but these results should be interpreted with caution as they may underestimate indirect costs of longer in-water times due to net ruptures and reduced fish growth. There is thus a trade-off between the increased likelihood of these higher indirect costs and the cost reductions of an optimistic net change policy. A graphical depiction of the cost variations for in-water times is given in Figure 3.

4.2.4. Sea lion net change scheduling. As already explained, one day a week in the 24-week scenario was devoted exclusively to changing sea lion nets. The company was interested in determining the impacts of altering this parameter by scheduling a 'dedicated week' for the activity every four weeks. Thus, the original scenario was evaluated with this single modification in which weeks 4, 8, 12, 16 and 20 were wholly turned over to sea lion net change. Cage net changes could then be made on all 5 days in each of the remaining weeks. As can be seen in Table 8, the global costs for the two policy

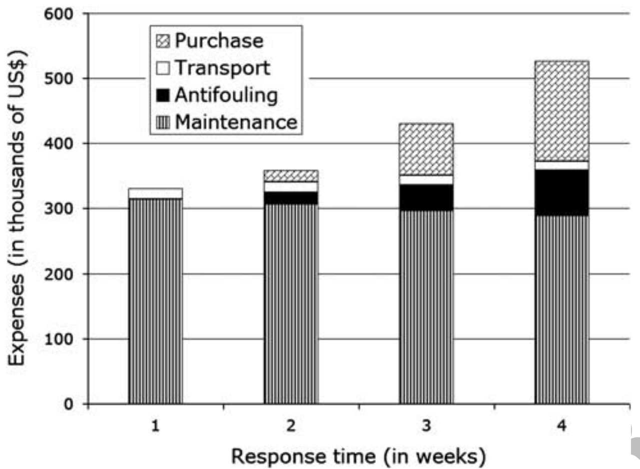

Figure 2 Cost variation as a function of maintenance facility response time.

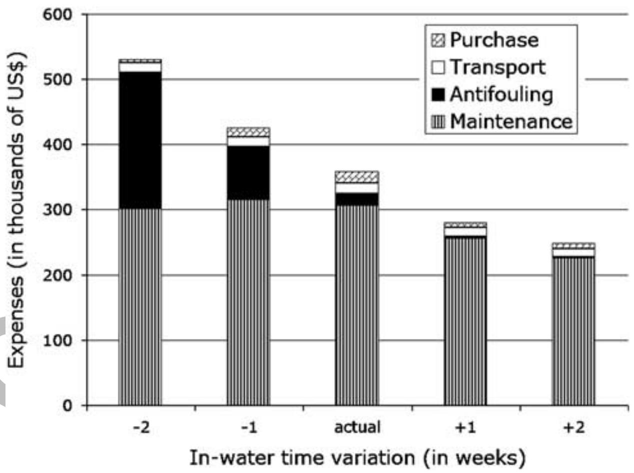

Figure 3 Cost variation as a function of net in-water time.

Table 7 Sensitivity analysis results for net in-water time

In-water time variation	*Expenses (in US$)*					*Savings (%)*
	Maintenance	*Antifouling*	*Transport*	*Net purchase*	*Total*	
−2 weeks	301 380	208 530	4 737	15 719	530 366	−48.26
−1 week	314 980	80 593	13 409	16 414	425 396	−18.92
actual	305 930	18 268	15 779	17 745	357 722	
+ 1 week	256 050	2 283	8 672	13 318	280 323	21.64
+ 2 weeks	225,950	2,283	8 672	11 784	248 689	30.48

Table 8 Results obtained using dedicated weeks for sea-lions nets changes

	Dedicated weeks	*Expenses (in US$)*				
		Maintenance	*Antifouling*	*Transport*	*Net purchase*	*Total*
Manual	No	327 120	26 793	18 260	63 511	435 904
Model	No	305 930	18 480	15 779	17 745	357 722
	Yes	308 050	25 119	16 304	22 883	372 356

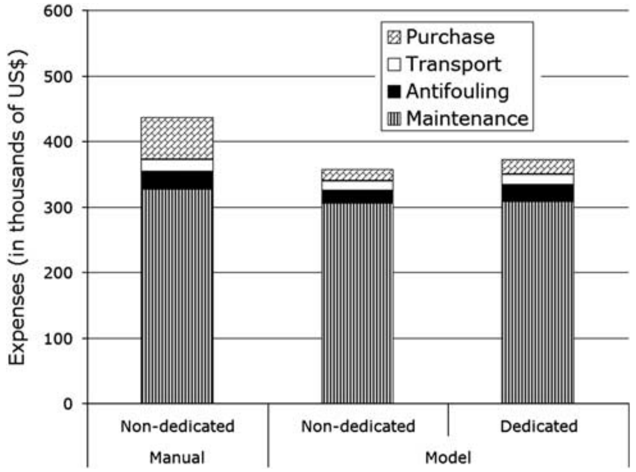

Figure 4 Cost variation as a function of sea lion net change scheduling.

alternatives as calculated by the model are broadly similar, the 'dedicated week' approach generating an additional 4% in expenses but still costing 15% less than under manual planning, which only considers the one-day-a-week option. A graphical depiction of these cost variations is given in Figure 4.

The results of these sensibility analyses clearly indicate that the parameters with the highest marginal impact are the net in-water time limits (Table 7) and the maintenance facility response time (Table 6). Regarding net in-water time, salmon farm decision-makers must determine the correct values for this variable based on the behaviour of the relevant local factors. Expert judgement is thus essential to the process.

As for maintenance facility response times, they should be managed by the operator in such a way as to eliminate variations affecting the defined strategies and reduce the need for making decisions under pressure on antifouling treatments and net purchases.

In contrast with the above parameters, variations in net boat capacity and maximum daily activities made little difference to total costs (Table 5).

Finally, it was demonstrated that the adoption of a 'dedicated weeks' schedule for sea lion net changes also had no major cost impact (Table 8), but may nevertheless be useful in improving company logistics. Multiexport, for example, reports various cage net ruptures a year caused by sea lions with the consequent loss of many kilos of salmon volumes, not to mention the headache of removing the animals from the cages. Dedicating certain weeks exclusively to checking and changing the predator nets may help reduce these problems and stabilize logistics generally.

5. Conclusions

This study presented an integer programming tool for scheduling the maintenance, repair and periodic changing of salmon farm cage nets. The application, implemented in 2008 as a pilot project hosted by a salmon farm operator in southern Chile, was shown to offer multiple advantages over manual scheduling methods. These advantages may be summarized as follows:

- The tool delivers significantly superior solutions compared to manual methods and provides valuable support for better planning. In the reported implementation, the tool proved capable of generating a long-term 24-week plan for an operator that had previously defined its solutions manually for lengthy periods which in practice had to be fine-tuned once or twice a month.
- An operating plan generated by the tool can be readily redefined at any time during its execution to adjust for unforeseen circumstances that might affect its optimality, or even its feasibility, by simply rerunning the application with the new scenario incorporating the changed circumstances.
- The tool helps analyse a question that has long gone unresolved in the industry: whether net antifouling treatments are economically justifiable. Our preliminary results show that the answer depends on the length of the net in-water period and the time of year (due to sunlight intensity). In general terms, it was found that treatment is only minimally justifiable in the summer months and not at all during the rest of the year. This finding confirms the intuitive suspicions of the company experts.
- The tool can evaluate how many net boats are required and the risk involved in contracting a number just sufficient to meet demand. Efficient use of the boats is extremely important given the high cost of boat rentals and associated personnel (mainly divers).
- The tool can determine whether sea lion net changes should be scheduled on a one-day-a-week or entire 'dedicated weeks' basis.
- The tool can evaluate personnel training policies implemented at different points in the supply chain by calculating the benefits of efficiency improvements in net boat use and maintenance facility response times. This was illustrated in the sensitivity analyses presented in this study.
- A positive, if indirect, consequence of implementing the tool is that operators will find themselves obliged to improve their operating practices and keep full and systematic data on net use and maintenance.

The various benefits just enumerated are thus provided by a single tool that supports decision-making processes for the efficient maintenance of salmon farm cage nets. The potential for savings using the tool over the long run is particularly significant. In our pilot project, implemented for just one of the host operator's geographical operating areas containing 6 of its 30 farm centres, the cost reduction was 18%. Company experts estimate that at the remaining 24 centres, the tool could generate economies of 10 to 20%. This suggests that expected global savings for the firm would range from 500 thousand to 1 million dollars annually. Note that the costs covered by the model represent about half of the operator's 10 million dollars in annual expenditure on net maintenance. Excluded were the expenses for boat rental (including divers) and land transport, both determined by fixed annual contracts, as well as sea lion net maintenance, which the firm prefers to manage separately.

In addition to the contributions demonstrated explicitly in this study, other of the tool's potential improvements that are difficult to quantify should also be considered. These include increased fish growth due to less stressful cage conditions and cleaner nets, less net damage (a single torn net can mean losses of about 200 000 dollars and a serious environmental impact due to the fish escape), better working relationships with farm centres' suppliers (maintenance facilities and net boat operators), reduced planning personnel requirements, and shorter scenario generation times, the latter meaning faster and more efficient evaluation of multiple scenarios. Whereas with manual methods, generating a single complete scenario may occupy an entire day, the tool cuts the time required to a few minutes. Furthermore, the application generates better quality planning with greater detail given that it delivers solutions for each individual cage while manually produced solutions only plan the centre as a whole.

Another interesting aspect of the tool is that it enables expert users to 'force' decisions, thus enabling other factors not explicitly modelled such as changing sea lion nets to be incorporated. The application can also take into account unforeseeable or difficult-to-model events like labour disputes, or add past actions in order to fit the model more closely to actual operating conditions. Such adaptability makes the tool much more applicable to the full gamut of observed situations, an important advantage given that the complexity of real-world environments is always much greater than anything a modeller's original design can capture.

Another noteworthy aspect is the tool's user-friendly interface, without which its daily use would be impractical even with its many other obvious benefits. This is a key element in using the application for tasks like the automatic generation of net use graphics, incurred cost data and net maintenance planning forms. The interface also allows the user to input previous planning histories, readily set variable values, and employ different colours for displaying net treatments or any other items that could be conveniently represented using this graphical capability.

The views of pilot-project host Multiexport on the application have been expressed by its operations manager, Rodrigo Niklitschek: 'The utility of the tool is enormous. Once a company reaches a certain size, the number of variables affecting net management optimization makes it impossible to do manually. It's very common to see operators making decisions in which only certain variables are controlled, without optimizing the whole set of net systems. The tool's rapid response time and its ability to analyze multiple scenarios and generate realistic results allow users to make clear and logical decisions'. Clearly implicit in these comments is that even though the project was implemented at just one firm, the proposed tool would be suitable for adoption by any Chilean salmon producer.

As was noted in the Introduction, the Chilean salmon farming sector was hit in 2008 by a major crisis due to the ISA virus, which seriously slowed fish growth and may have also increased mortality. The damage to the industry laid bare the irrational manner in which it had grown, with little thought for the use of technological tools in daily management of operations. This considerably aggravated the consequences of the virus. Coming on top of a worldwide economic recession, the crisis forced industry operators to drastically cut back on production workers and reduce the number of farm centres and personnel not directly involved in the production process. In this context, Multiexport was obliged to suspend implementation of the tool and modify certain of its maintenance operating processes. As a result, the application was not in use at the time of writing but implementation is expected to recommence once conditions in the industry return to normal.

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