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A SIMULATION MODEL FOR ASSESSING FISHING FLEET PERFORMANCE UNDER UNCERTAINTY

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ABSTRACT

This paper presents a simulation model for assessing the impact of myopia and catch rate variability on the cost-performance of a coordinated fishing fleet. The trawler dispatching problem faced by integrated fish-processing firms in the Canadian Atlantic Groundfish industry, is modelled using the simulation language SLAM II. Results obtained for three realistic test problems highlight the usefulness of such a model to decision makers in the fishery.

1. INTRODUCTION

The trawler routing problem is a short-term planning problem faced by integrated fishing firms in the Atlantic groundfish industry. It involves the dispatching of a coordinated fishing trawler fleet in order to satisfy the demand for various species at a number of geographically dispersed fishing processing plants. The primary objective of the planning problem is to satisfy all species requirement over the planning horizon at minimum cost. To achieve this, several trawler trips must be designed. A trip is defined as the movement of a trawler between two successive plants through intervening fishing grounds (stocks), with catching activity taking place at each fishing ground.

Without loss of generality, a dispatched trawler leaves a plant (its origin), and steams to a fishing ground. There it undertakes a specified level of fishing activity directed at a given species. Once the fishing activity is completed, the trawler may remain in its current location and fish another species, steam to another fishing ground to catch the same or another species, or steam to a plant where it off-loads the catch in its hull. Hence, the output of the trawler dispatching process is a set of trips for the individual trawlers in the fleet with catch deliveries that satisfies species demand requirements at all of the firm's plants.

The trawler dispatching process is marred by the uncertainty in catch rates, the species breakdown on fishing grounds, and by the performance characteristics of the trawlers in the fleet. The deterministic version model of this complex decision process is modelled as a mixed-integer program in Millar [1990]. To model the uncertainty in trawler dispatching would require a stochastic mixed-integer program which would be quite difficult to solve. Given the need to understand the impact of parameter uncertainty on fleet performance and the difficulty of solving stochastic mixed-integer programs, we resort to the application of simulation methodology.

In this paper, we present a simulation model of a trawler dispatching process. The model in some ways resembles the dispatching process used by fishing firms. The purpose of the model is to assess the impact of catch rate uncertainty and single-step real-time decision making on fleet performance. By single-step real-time dispatching, we mean that the trip components for a given trawler is determined one step at a time. For example, a trawler may be dispatched to a given ground to fish 300 tons of cod. Its next move, i.e., whether to return to port or move to another fishing ground, is not decided until its performance on the ground has been observed. This is in contrast to the look-ahead capability available in deterministic fleet dispatch.

The simulation model is not a descriptive model for an existing company, but a reasonable representation of the dispatching process which takes place. There are two categories of differences between our model and the process for a firm. First, in real time, external factors (market demands, plants demands, etc.) can influence the next set of decisions made by the company's dispatcher. Secondly, we are not aware of the exact decision rule(s) used by company dispatchers.

1.1 Literature

To our knowledge no trawler simulation models for integrated fishing firms have been reported. We have observed, however, several simulation experiments conducted on behalf of the Department of Fisheries and Oceans (DFO), NSRF [1971], NSRF [1972], and NSRF[1973]. These models focus primarily on the mid-water trawling problem. In each case only a single trawler is used. The objective in NSRF [1971] was to evaluate the impact of an information system for skippers. In NSRF [1973] the objective was to evaluate the operating potential of trawlers equipped to catch redfish and herring, and in NSRF [1972] the objective was to evaluate the effectiveness of various trawler designs. None of these models was developed in the context of an individual firm, and therefore these models simply focused on catching efficiency without consideration for quotas, plant requirements, multi-trawler interactions, and transportation costs.

Other simulation models include the works of Bjorndal [1981] who simulated the fish meal industry in Norway, and Jensson [1981] who modelled the Capelin fishery in Iceland using a simulation model. Both of these models focus on macro issues in the fishery. Unlike Bjorndal and Jensson, Jonatonsson and Rauhawa [1986] modelled a fish processing facility to assess performance issues. Unlike the model developed in this paper, their model looks at processing while our model studies catching activity.

The rest of the paper proceeds as follows. In the next section the primary features of the simulation model are delineated. In section 3.0 the logic of the simulation model is presented and its implementation using SLAM II is outlined in section 4.0. In section 5.0 we present computational results for three test problems. The paper concludes with some remarks about the simulation model and its possible extensions.

2. PRIMARY FEATURES OF THE MODEL

In this section we discuss the primary features which make up the simulation model. The features considered here include: fish abundance, trawler activity, species demands, information feedback, and the decision maker.

2.1 Fish Abundance

The availability of fish on a fishing ground can be modeled as distribution for catch rates combined with a distribution for species composition. Ideally the distributions should be a function of time, stock, stock-size, and trawler type. A common type of distribution used for modeling catch abundance is the lognormal distribution (see NSRF[1971], [1972], and [1973]). While much historical data on the exploitation of NAFO fishing grounds is available in bulletins issued by the organisation, the data cannot be used to provide firm-specific catch rate and species-mix distributions.

For our simulation model, there was insufficient historical data to allow the development of empirical distributions for catch rates and species mix. Instead, we assume a lognormal distribution for catch rates as a function of stock and trawler type. Knowledgeable personnel in the industry estimated the means for the distributions. The standard deviation is set as a fraction α of the mean for the distribution. This relationship between the mean and the standard deviation is adopted from the simulation models reported in NSRF [1971], [1972], and [1973].

We assume fish abundance over time for a given fishing ground is serially correlated. This makes sense as dramatic fluctuations in catch rates are highly unlikely. In reality catch rates slowly decrease or increase over time. We employ a correlation function of the form

$$\sigma_t = \alpha S + (1-\alpha)\,\sigma_{t-1}$$

in our simulation model. A similar function was employed in NSRF [1971]. Referring to a 12-hour time frame as a period, we define the following.

σ_t - catch rate in period t,

σ_{t-1} - catch rate in period t-1,

S - a realisation from the catch distribution,

α - correlation factor ($0 \leq \alpha \leq 1$).

The parameter α controls the rate of change of catch rate. Small values of α imply that the catch rate in period t is determined largely by the previous catch rate. A large value, conversely, implies that the catch rate for period t is determined largely by the sampled catch rate.

It is important to attach a 'life' to catch rates, i.e., the time during which the catch rate sampled on a ground will not change. For the purpose of our model, we assume a 12-hour life for catch rates, and a correlation factor of 0.4. Similar values were used in NSRF [1971].

2.2 Activities of the Trawler

The fishing trawler can undertake one of several activities. Some activities have a single predecessor or successor, while others may have several possible successor decisions. Table 4.1 shows a transition matrix for the activities of the trawler. A '1' indicates that the activity in the column is a possible successor to the row activity. Rows with more than one '1' imply the need for a decision upon completion of the row activity. Possible trawler activities are defined as follows.

loading - refers to the loading of supplies and all necessities at the port of departure
steaming out - steaming from port of departure to next location
fishing - the process of dragging a net to catch fish
shifting - steaming from one fishing ground to another
dodging - steaming away from bad weather
steaming home - this refers to the steaming activity from a stock to the landing port
unloading - refers to unloading the catch onboard a trawler
refit - refers to maintenance activity on a given trawler

In our simulation model, the decision to dodge never has to be made as weather conditions are not incorporated. Also, given the short-term planning horizon, refitting activity, which can often take weeks, is not considered in our simulation model. We assume the trawlers that are available at the beginning of the simulation period are also be available throughout that period.

2.3 Information Feedback

Information feedback is an extremely important feature in the trawler simulation model. Each trawler during the course of the simulation provides the 'dispatcher' in the simulation model with information on its location, the observed catch rates, current catch in the hold, and trip time left. This information is used when making subsequent dispatching decisions.

Table 1. Activity Transitions for a Fishing Trawler (NSRF[1971])

		Activity to Follow							
Activity Completed	No.	1	2	3	4	5	6	7	8
Loading	1	0	1	0	0	0	0	0	0
Steaming out	2	0	0	1	0	1	0	0	0
Fishing	3	0	0	1	1	1	1	0	0
Shifting	4	0	0	1	0	1	0	0	0
Dodging	5	0	0	1	0	0	0	0	0
Steaming home	6	0	0	0	0	0	0	1	0
Unloading	7	1	0	0	0	0	0	0	1
Refit	8	1	0	0	0	0	0	0	0

3. OUTLINE OF THE SIMULATION LOGIC

The logic of the discrete simulation model is outlined in the following paragraphs.

3.1 Data Input and Initialisation

The first step in the simulation of the trawler routing problem is the accessing of a fisheries data base to obtain information on trawler availability, and trawler parameters such as capacities, costs, trip lengths, stock and port restrictions, locations, plant species demands, stock quotas, stock to stock and stock to port distances, and initial estimates of catch rates and standard deviations for each trawler-stock combination. Once the data base is read, several variables and counters are then initialised. Eg.,

1) Trawler status variables
   - trip counter
   - current catch
   - current trip length
   - location
   - current activity
2) Plant status variable.
   - current species demands
3) stock status variable.
   - size of the current quota

The variables used in the generation of output statistics are also initialised.

3.2 Trawler Dispatch

At any time, the primary decision is to determine the next activity for one or more of a number of available trawlers. The decision made is one of the following: i) dispatch an empty trawler to a new fishing location, ii) have a trawler shift from its current fishing ground to another, and iii) have a trawler steam inward from its current fishing ground to its destination port.

Assume a set of unsatisfied demands at each of a subset of ports, and also assume there is a set of available trawlers. The dispatching mechanism (DM) determines the next stock-port combination to be served. Once the stock-port combination is selected, the trawler to be assigned to the task is subsequently selected. This selection is based on a weighted marginal-cost criterion. The selected trawler is assigned a catching task based on the current estimate of the catch rate for the fishing ground, the plant-species requirement, the remaining quota for the stock, and the capacity of the trawler. The DM then routes the trawler to its currently assigned stock. At this point the current information on the trawler with respect to its route includes a specified stock visit, a catching task, and a landing port. Noting the current catching assignments, and temporarily updating quotas and unsatisfied species-demand, the dispatching process is repeated until as many trawlers as possible are assigned.

The DM is triggered at distinct points in time. These points are as follows: i) when a trawler arrives at a stock or port, ii) when a trawler has observed a minimum of 48 hours of catching activity, iii) when a trawler has completed its catching assignment at its current fishing ground, and iv) when a trawler has completed in-port activity after its last trip.

On arrival at a fishing ground, the catch rate generator produces an observed catch rate for the fishing ground using the appropriate catch rate distribution. If the observed catch rate is 'acceptable', then the trawler attempts to complete its catching task on the fishing ground. Based on the observed catch rate and other pertinent factors, the actual catch for the trawler is determined. If the actual catch differs from the initial allocation, then the appropriate adjustment is made in the unsatisfied plant-species demand.

If the sampled catch rate for a fishing ground is 'unacceptable', say 30% or less of the mean catch rate for the fishing ground, then the trawler fishes for a 24 hour period after which the DM considers the possibility of shifting grounds for the trawler. Two types of shifts are considered. The trawler may be shifted to another fishing ground where it can attempt to land the same species it has been assigned, or it can be shifted to another ground to fish an entirely different species. The decision for this trawler, in order to be cost-effective, takes into consideration the availability of other trawlers at the time of decision-making. In other words, where the DM is concerned, this trawler is simply another available trawler for dispatch, taking into consideration its current location, fish on board, trip time left, and other pertinent factors. The fact that the trawler is already at sea increases its chances of being shifted to another fishing ground. However, it is conceivable that the trawler could remain at its current fishing ground, be shifted to another fishing ground, or routed to its landing port.

The number of shifts a trawler is allowed on any given trip may be restricted. It is impractical to allow a trawler to shift any number of times. We allow a maximum of two shifts per trip.

After a trawler has completed its current catching task (i.e., the level of catch it was assigned), the trawler can either steam to another fishing ground, or steam to its landing port. The decision is made by the DM. If the hold capacity is filled or the trip length restriction is binding, then there is only one decision, i.e., steam to landing port. If on the other hand sufficient time and capacity is available, then the DM treats the trawler as being available, and determine whether it should land its current catch or shift to another fishing ground.

Upon arrival at a landing port, a trawler off-loads its catch and experiences a 48 hour in-port delay. This delay is necessary in order to clean, refuel, re-ice, re-crew, and restock the trawler with necessary supplies. During the 48 hour in-port period, the trawler is not available for dispatch. After in-port activity has been completed, however, the trawler once again becomes available for dispatch.

3.3 Output Generation

The primary purpose of the simulation model is to assist in the assessment of the impact of myopia in dispatching, and uncertainty in catch rates. The model generates data on the number of trips for each trawler, the length of each trip, the total time a trawler was engaged in fishing and steaming activity, the number of stocks fished on each trip, the trips for each trawler, the cost of each trip, and the catch for each stock visit for each trawler. Given all this information, a host of comparisons can be made between the results of the simulation model and the results obtained from the implementation of the route-building heuristic on corresponding deterministic catch rate data.

A flow diagram of the simulation logic is shown in figure 1.0

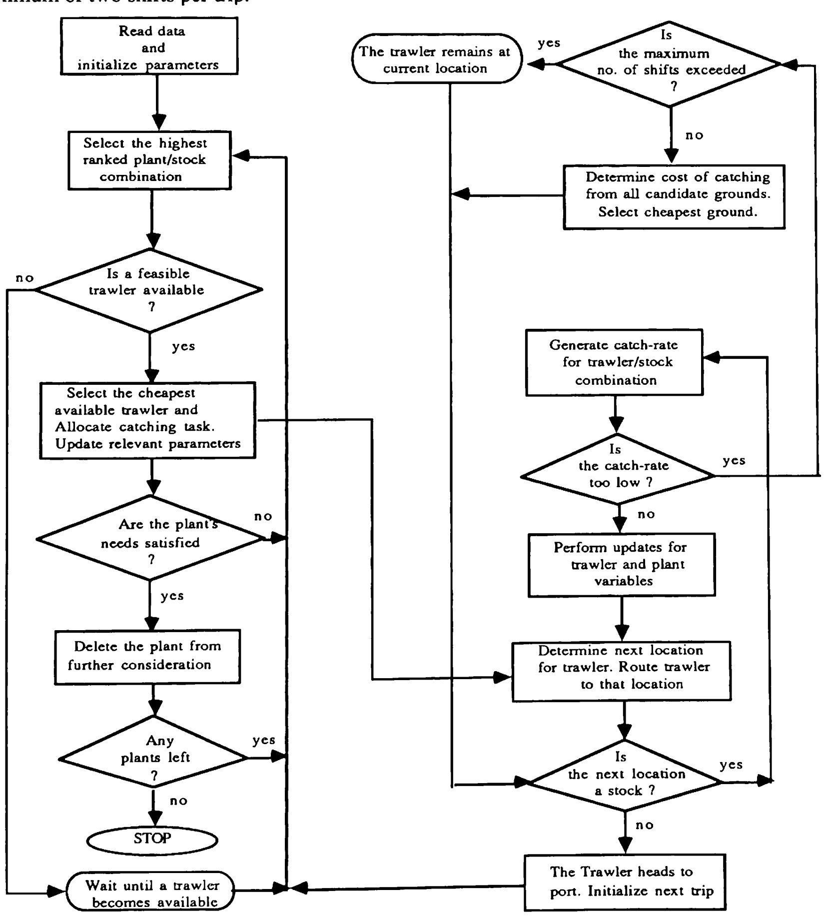

Figure 1. The Flow Logic of the Simulation Model

4. THE COMPUTER MODEL

To execute the simulation for the trawler dispatching problem, we employ the SLAM II simulation language developed by Pritsker [1986]. We exploit the capability of the language which allows the incorporation of several world views within a single computer model. Our computer model combines two world views, the process orientation and the event orientation. In the event orientation, the trawler routing problem is modelled by defining the changes that occur at discrete event times. In the process orientation, the problem is modelled by the flow of entities (the trawlers) through a network.

4.1 The Network Model

The SLAM II network model is shown in figure 2.0

Due to the complexity of the trawler routing problem, it is not possible to execute all the necessary event logic by various nodes of the process orientation of SLAM II. Hence several user-written routines are designed. These routines are interfaced with the network model through an EVENT node. The arrival of an entity at an event node invokes a user-written subroutine. The subroutine subsequently performs all the necessary event logic in accordance with its design.

The SLAM II network model uses five event nodes identified by the labels: UPDAT, DEC, REDY, PSEL, and VSEL. Each node is associated with an event code which matches the event node with a particular subroutine.

Event UPDAT is associated with a subroutine responsible for sampling a catch rate, allocating catching activity, updating plant-species requirements, updating quotas, computing costs, updating stock rankings, and so on. Event DEC is associated with a subroutine responsible for determining whether the trawler should steam to its landing port or shift to another fishing ground. If the decision is to route the trawler back to port, then an entity with all the attributes of the trawler is sent to node INWD. On the other hand, if the decision is to steam to another fishing ground, then an entity with the attributes of the trawler is sent to enter node OTWD. Event PSEL is associated with a subroutine responsible for selecting the next stock/port combination for service. Once the combination is determined, an entity flows between PSEL and VSEL. This entity is not a trawler entity, but rather an entity used solely to invoke the subroutine associated with VSEL. Event VSEL is associated with a subroutine responsible for selecting a trawler from the available trawler set to service the stock-port combination selected by PSEL.

Event REDY is associated with a subroutine responsible for reinitialising the values of trawler-specific variables such as trip time, location, capacity, fish onboard, and so on. The trawler is considered for redispatch by the event subroutine associated with VSEL. If selected, the trawler reenters the network as an entity through enter node OTWD.

There is one other node not discussed so far. The node labelled GN1 is called a GOON (go on) node. Its function is primarily to separate activities for the purpose of clarity. The trawler, on its inward leg, would take the branch between node INWD and GN1 with a duration given by attribute(5). The arrival of the entity at node GN1 signifies the arrival of the trawler at its landing port. The in-port activity is represented by the branch between GN1 and REDY with a duration specified by attribute(7).

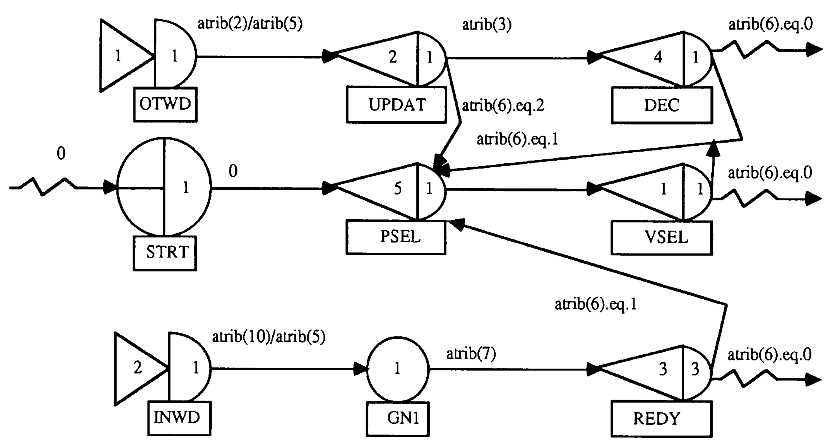

Figure 2. SLAM II Network Model

In our network model individual trawlers represent the entities which flow through the branches of the network. Each entity has an attribute vector associated with it. The attributes are defined in table 2.0.

The entities for the network are created at the beginning of a simulation run through the use of a CREATE node. The CREATE node in figure 2.0 is identified by the label STRT. It creates a single entity at the start of the simulation run which in turn triggers the discrete-event logic to generate the entire fleet of trawlers, with each trawler in the fleet having an initialised attribute vector. The maximum number of entities in the network, therefore, is bounded by the size of the trawler fleet.

The entities (trawlers) are introduced into the SLAM II network model at two points. One of these points represent the commencement of the outward leg of a trip of a trawler, while the other represents the commencement of the inward leg of a trip of a trawler. The entry of the entities into the SLAM II network is facilitated by what is referred to as an ENTER node. The ENTER node for the outward leg is labelled OTWD, and for the inward leg INWD. The ENTER node acts as a one way interface between the discrete part of the simulation model and the network part of the model. Entities flow from the former into the latter.

Once the entities are in the network, they flow between the nodes of the network through activity branches. An activity branch is responsible for marking the passage of time. The fishing and steaming activities of a trawler, therefore, are denoted by activity branches in the network. The duration of the activity is specified by one of the elements of the attribute vector of an entity. Attribute(2) for a trawler, for example, specifies the time to steam from its port origin to its assigned fishing ground. Likewise, attribute(10) specifies the time to steam from its current fishing ground to its landing port.

4.2 The Event Orientation

The complexity of the trawler routing problem precludes the sole use of the network orientation feature of SLAM II for modelling the problem. The predefined logic of SLAM II network nodes is inadequate, since flexibility is required to model the changes in the system's status as a result of trawler activity. Fortunately, SLAM II makes it possible to incorporate both the process and event orientations in a single model. The world orientations are interfaced by the use of the EVENT and ENTER nodes which have already been mentioned.

Table 2. A Description of SLAM II Nodes and Variables

Variable/ Node Label	Definition
Atrib(2)	- a variable which stores trawler number
Atrib(3)	- a variable indicating duration of fishing activity
Atrib(4)	- a variable indicating current stock for the trawler
Atrib(5)	- a variable indicating outward or inward steaming time
Atrib(6)	- a binary decision variable
Atrib(7)	- a variable indicating inport turn around time
Atrib(8)	- a variable indicating the volume of fish to be caught by the trawler entity
Atrib(9)	- a variable indicating the landing port for the current trip
OTWD	- a node indicating trawlers entering the network on the outward leg
INWD	- a node indicating trawlers starting a steaming leg into port
UPDAT	- a node for invoking an updating subprogram
DEC	- a node for invoking a subprogram which makes decisions about the next move of a trawler whose trip is already in progress
PSEL	- a node for invoking the process of selecting the next port for service and also the next stock
VSEL	- a node for invoking the process for selecting the next trawler whose trip is to be constructed or extended
REDY	- a node invoking a subprogram which is responsible for initialising the next trip for a trawler
GN1	- a node separating the inward steaming activity from the inport activity

Our simulation model must be verified to ensure that code works as intended. SLAM II makes that task simple with its trace capability. A trace report allows the modeller to follow entities as they flow through the network. Any anomalies in the flow of the entities are indications of faulty logic.

Face validation of the model is carried out by comparing trawler specific statistics generated by the simulation model with trawler-specific statistics generated from historical landings obtained from one company in the industry.

5. COMPUTATIONAL RESULTS

5.1 The Test Problems

Our test company owns 40 trawlers, 9 plants, and harvests 6 species from 36 stocks. A stock is the a species within a geographical area. For each stock, the company is allocated a quota that it can catch at any given time during the year. The company processes 5 broad categories of products for each species.

The company provided historical trawler landings for the years 1983-1985. We extracted three test problems, one for each year. The three problems are referred to as T1, T2, and T3 respectively.

5.2 Simulation Results

To assess the impact of single-step real-time decision making, we examine, for a given set of catch rates, the difference between the solutions obtained by the heuristic methodology in Millar [1990], henceforth referred to by HEUR, and the simulation results obtained with zero variability for the catch rates. To assess the impact of catch rate variability on real-time dispatching, we assume a lognormal distribution for catch rates and execute the simulation model for a given set of distribution parameters (mean and variance of catch rates). The difference between the real-time solution with zero variability and real-time solution with variability is attributable to the variability in catch rates. In the latter, the observed catch rates are stored. This information is then used by HEUR to construct an alternative fishing schedule. The gap between the solutions generated by the simulation model and HEUR helps to reaffirm the need for improved planning techniques for dispatching the trawler fleet.

Table 3.0 shows a comparison between the myopic results, the company's solutions, and the solutions generated by HEUR for the three test problems T1, T2, and T3. These results are based on deterministic catch rates. The myopic results are slightly better than the company's solutions, 0.19%, 5.4%, and 2.0% respectively, but significantly worse than the solutions obtained by HEUR, 9.8%, 9.8%, and 8.45%. This inadequacy is worth millions of dollars.

Table 3. Myopic Results for Problems T1, T2, and T3 (in $)

Problem	Heuristic Solutions $\$ \times 10^6$	Simulation Results $\$ \times 10^6$	Firm's Solutions $\$ \times 10^6$
T1	18.55	20.57	20.61
T2	24.72	27.44	28.92
T3	18.90	20.64	21.06

The differences between the heuristic solutions and the solutions of the simulation model can be attributed to the lack of look-ahead capability in the simulation model. Given that the dispatchers in the industry dispatch the fleet in much the same way, the potential losses are quite significant. This is shown in table 3.0.

Table 4.0 shows results based on 30 simulation runs for the myopic model with catch rate variability. The observed results show a fair amount of stability in the cost of the solution with an average coefficient of variation of less than 0.4%. When these results are compared to the solutions obtained by applying HEUR to the observed catch rates from each simulation run, we observe differences ranging between $1.5 million to $2.6 million as shown in table 5.0.

Table 4. Simulation Results Based on 30 Runs

Problem	Mean of Simulation Runs ($\$ \times 10^6$)	Standard Deviation ($\$ \times 10^6$)
T1	20.55	0.099
T2	27.44	0.099
T3	20.55	0.072

To further test the impact of catch rate variability, we simulate a dispatching problem with different standard deviations for the catch rate distributions. Recall that the standard deviation for the lognormal distribution used in the simulation model is expressed as a fraction γ of the mean of the distribution. In other words, γ is the coefficient of variation for the distribution. We vary the standard deviation for the catch rate at each stock simultaneously, between 20% and 60% of the mean. The results are shown in table 6.0. The percentage change in cost is the difference between the simulation solution and the deterministic solution (zero variability) of $2,271,925 expressed as a percentage of the deterministic solution.

These results, obtained for a problem with a one-month planning horizon, show a general increase in cost as variability increases. The increase in cost, however, may not be monotonic as sampled catch rates with large deviations from the mean may tend to cancel out the effects of large and small catch rates. The average increase in cost is 3.24%, representing an average increase of approximately $0.75 million. Increasing variability in catch rates also meant increasing the average number of trips and the average amount of vessel time required to land the same quantity of fish.

Table 5. Evaluating the Cost of Myopia in Fleet Dispatch

Problem	Mean cost for Simulations Results ($ x 10^6)	Mean cost Heuristic Solutions ($ x 10^6)	DIFF ($ x 10^6)
T1	20.554	18.624	1.930
T2	27.439	24.863	2.576
T3	20.553	18.988	1.565

Table 6. Summary of Cost Statistics Under Varying Catch Rates

Coefficient of Variation (γ)	COST($) $ x 10^6	INCREASE IN COST (%)
0.20	2.336	+ 2.81
0.30	2.336	+ 2.82
0.40	2.340	+ 3.00
0.50	2.363	+ 4.02
0.60	2.353	+ 3.55

6. CONCLUSIONS

In this paper we have outlined and demonstrated a dynamic model for assessing the impact of single-step dispatching on the cost performance of the trawler fleet, as well as the impact of catch rate variability on catching costs. Though the dynamic model is not a descriptive model of an existing dispatching process, it is, we believe (based on conversions with an industry official), not dramatically different from what is being done in the industry. Hence the results obtained from this model can be used to make some generalisations about the industry, particularly if it can be shown that the model can out-perform a company's experience on a given test problem from historical records.

The results obtained show that myopic dispatching of the fleet can lead to significant increases in the the cost of satisfying species requirements at the firm's plants. The results obtained for the experiments which incorporated variability in catch rates show that cost increases with increasing variability, but not in a dramatic way.

The simulation model can be used to examine other performance measures for the fleet. These measures include fleet utilisation, average time spent fishing, average time spent steaming, the average number of shifts for a trawler, the average number of trips per trawler, and the average amount of fish caught for a trawler. Further extension of the model to reflect a realistic dispatching process allows it to be used to evaluate the value of perfect information. This information could ultimately be used to plan exploratory fishing missions. Finally, the model can provide the core structure for the development of a management game to assist decision makers in understanding the complexities of the fishery.

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