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Managing uncertainty in fishing and processing of an integrated fishery

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Abstract
This paper considers uncertainties in fishing trawler scheduling and production planning in a quota-based integrated commercial fishery. A commercial fishery faces uncertainty mainly from variation in catch rate, which may be due to weather, and other environmental factors. The firm attempts to manage this uncertainty through planning co-ordination of fishing trawler scheduling, catch quota, processing and labour allocation, and inventory control. Schedules must necessarily be determined over some finite planning time horizon, and the trawler schedule itself introduces man-made variability, which in turn induces inventory in the processing plant. This induced inventory must be managed, and is complicated by the inability to plan beyond the current planning time horizon. A simple constraint is introduced requiring beginning inventory to equal ending inventory of the planning period. This enables management to calculate a profit-maximizing safety stock that counter-acts the man-made variability due to the trawler scheduling. It is found that the variability of catch rate had virtually no effects on the profitability. Numerical results for several planning time horizon models are presented, based on data for a major New Zealand fishery.

Key words: Integer programming, trawler scheduling, fish processing, safety stock.

1 Introduction

A quota-based integrated commercial fishery that owns fishing trawlers, processing plants, and fish quotas is considered. The fishery faces uncertainty mainly from variation in the catch rate, due to weather, available quota, seasonality of fish stock and other environmental factors. By the seasonality in fish stock, it is implied that the catch rate of a single fish species may be different in different seasons of the year. The fishery tries to manage these uncertainties through planning co-ordination of fishing trawler scheduling, catch quota, processing and labour allocation, and inventory control. This paper investigates how to model the uncertainties in trawler scheduling and production planning due to variability in catch rate.

To overcome the difficulty of catch forecasts for a long time horizon, managers often use a shorter planning horizon than any reasonable estimate of the firm's real future

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time horizon. This results in end-of-planning-horizon effects, which provides suboptimal solutions. In particular, deterministic mixed integer linear programming (MILP) models tend to leave a zero inventory level in the final period unless a minimum final inventory level is prescribed (Dantzig 2004). Otherwise, the model will predict to process all of its landed catch as soon as it is available without considering the necessity of holding inventory and to sell the products for profit. There is no incentive to pay inventory holding cost if there is no need for safety stock. In real life, the fishery needs both initial and final inventory levels. Since, at the beginning of a planning horizon, the trawlers need at least two days for fishing and landing its catch. If there is no initial inventory available there will be no activities in the processing plant and all labour will have to sit idly until the trawlers land their catch. Again, at the end of a planning horizon, if there is no final inventory level, then the next planning horizon will face the same problem (Hasan 2008). So the fishery needs both initial and final inventory as safety stock.

The perishability of raw materials and products is another factor which has a significant influence on the inventory policy. The fishery inventory control is sensitive to fishing, processing and marketing decisions. The trawler schedule itself introduces man-made variability, which in turn induces inventory in the processing plant. This induced inventory must be managed, and is complicated by the inability to plan easily beyond the current planning horizon.

Safety stock has been widely used to overcome these problems, especially in material requirement planning systems (Wagner & Whitin 1958; Blackburn & Millen 1980; Fisher *et al.* 2001). In this paper, we propose a simple safety stock approach to deal with these end-of-planning-horizon effects due to variability of catch rate. This can enable management to calculate a profit maximizing safety stock that deals with the variability in catch rate and counter-acts the man-made variability due to the trawler scheduling. It is also investigated whether a deterministic model is appropriate, given the high variability of catch. A set of simulation experiments, varying the coefficient of variation and mean catch rates is reported. The catch rates are generated by means of normal and lognormal distributions.

In addition, two results are presented. A safety stock approach that deals efficiently with the end-of-planning horizon effect is presented and it is shown that the use of a more complicated stochastic integer program (Wallace 2000) is unnecessary, because the variability in catch rate of fish makes little difference to profitability to the fishery. Using the average expected catch in a deterministic model appears to be effective. Numerical results are reported for several planning horizon models based on data for a major New Zealand fishery.

The remainder of the paper is organised as follows. A literature review is presented in §2, followed by a brief illustration of the fishery environment in §3. In §4 the Integrated Fishery Planning Model (IFPM) in matrix-vector notation is presented. The safety stock approach to manage end-of-planning-horizon-effects due to variability in catch rate follows in §5. In §6–8, the sensitivity of profit due to variability of the catch rate is presented by means of simulation experiments that generates catch rates with normal distributions and lognormal distributions respectively. The coefficient of variation is ranged from 10% to 50%. The paper is concluded in §9.

2 Literature

Mikalsen and Vassdal (1981) developed a multi-period linear programming (LP) model for a one month production planning model to smooth the seasonal fluctuations of fish supply. The model was market-driven and incorporated the acquisition of raw material purchased, rather than acquired with their own fishing fleet. Jensson (1988) developed a product mix LP model to maximize profit of an Icelandic fish processing firm over a five period planning horizon. He addressed production planning and labour allocation for that processing firm but did not address any fleet-specific issue or quota issue. Gunn, Millar and Newbolt (1991) developed a tactical planning model for calculating the total profit of a Canadian company with integrated fishing and processing. Their model included a fleet of trawlers, a number of processing plants and market requirements. However, their model ignored the trawler scheduling and labour allocation in the processing firm. Millar (1998) analyze the impact of rolling horizon planning on the cost of industrial fishing activity. The author analyzed the rolling horizon planning for a MILP model which only addresses the fishing trawler scheduling of an integrated fishery.

This paper significantly extends on Hasan and Raffensperger (2006), which provided a mixed integer IFPM to model trawler scheduling, processing plans, and labour allocation. The model can be updated and run periodically to aid in the decision making process over some finite planning horizon. Partly due to the inability to solve large MILP models, and partly due to the inability to forecast catch and demand, the planning horizon is kept relatively short.

3 Fishery environment

The data used for the experiments are obtained from a major fishery in New Zealand. The fishery has a fleet of three trawlers. Two of the trawlers are small vessels which catch an average of 12 tons per day, take two to three days per fishing trip, but can go fishing for up to 21 days. The third trawler catches an average of 90 tons per day, takes 7 to 8 days per trip, and can be at sea for up to 60 days. The trawlers harvest 8 species of fishing during a year. In a running season, the trawlers harvest hoki, roughy, dory, ling, red cod, squid, barracouta and elephant fish. The company produces 10 different products over the year. For the fishery model, a 10 period planning horizon is considered. The fish that cannot be processed in a period remain in inventory and are available for the next period's production. Similarly, the product that cannot be sold in a period remains in inventory and may be sold in the next period. In the following four subsections quotas, trawler scheduling, processing, and labour allocation are briefly described.

3.1 Catch quota

A permit to fish, usually valid for one year, enforces a quota on the quantities of fish removed from the sea during that period (Clement 2004). The quotas may be issued for free, against a fee, or at a public auction to companies or individual vessels. In case the quotas are issued and not auctioned, the allocation is based on a specified reference called the quota base. To control the continuous decrease in fish supplies, the Icelandic government introduced quota regulation in 1984, and implemented it for nine main commercial species (Jensson 1988). This system was implemented for all commercial species in 1990. In 1986, New Zealand was the first country to use quotas on a broad scale in a multi-species fishery. Currently, this program applies to 32 species in 10 management areas of New Zealand (Clement 2004). Other countries that use individual transferable quota systems include Australia, Canada, Italy, the Netherlands, Japan and South Africa.

3.2 Trawler scheduling

A trip of a fishing trawler is the movement for the purpose of fishing from any landing port to a distinct fish stock, and again from that stock to the landing port. The trawler operating costs per period include the salary of the crew, diesel cost, and average maintenance of each trawler. These costs vary according to the trawler class. Since the company owns the trawlers, the company pays the crew a salary. Since the trawler operation cost is fixed, we may assume that the landing price that the fishery pays to each trawler for each species and time period is zero.

3.3 Processing

When a trawler arrives at the freezing plant, the fish are inspected and graded by size and quality. The fish are unloaded, transported to the processing plant, and then processed according to the type and quality of the fish. At the plant, processing operations include cleaning, cutting, filleting, wrapping, skinning, forming, coating, grinding, drying, packing, and freezing. Major products include filleted, gutted, headed and gutted, dressed, fish sticks, fish blocks, *etc.* Heads and offal, together with other scraps and cuttings from the fish, are converted to fish meal.

3.4 Labour allocation

The fishery under study provided the required labour hours per kilogram of product in different work centres for all raw materials and product, the wage rate for regular and overtime labour hours, the lower and upper limits of the available labour hours, the lower and upper limit of the available overtime labour hours, and the available machine hours for this fishery. Employees may work in any work centre.

3.5 Planning horizon

The fishery gets the fish quota allocation for each year, resulting in a planning horizon of one year. To overcome the difficulty of catch and demand forecasts for a long time horizon, managers use a shorter planning horizon than any reasonable estimate of the firm's real future time horizon. The procedure of updating forecasts and solving the problem periodically is referred to as a rolling time horizon approach. The planning horizon is shortened due to the inability to solve large MILP models and the inability to forecast catch rates and demand.

4 Structure of the IFPM and problem generation

The quota-based integrated commercial fishery that owns fishing trawlers, processing plants, and fish quotas is investigated. They need an optimal trawler schedule for fishing and processing. The processing plant starts processing when the trawlers land their fish. The fishery faces uncertainty mainly from variation in catch rate, due to weather, available quota, seasonality of fish stock and other environmental factors. Since the managers often use a shorter planning horizon than a reasonable estimate of the firm's real future horizon, the end-of-planning-horizon effects cause suboptimal solutions.

The IFPM consists of a trawler scheduling and a processing subproblem along with side constraints containing variables from both the subproblems. For further details of the model, the readers are referred to Hasan & Raffensperger (2006). The structure of the model is given in matrix-vector notation. The parameters may be defined as follows. Let

- $\boldsymbol{c}^1$ be the unit profit of trawler operation,
- $\boldsymbol{c}^2$ be the unit profit of trawler raw fish inventory,
- $\boldsymbol{c}^3$ be the unit profit of trawler fish processing,
- A^0 be the quantity of fish landed per trip in each period,
- D^1 be the mass balance coefficients on each trawler in each period,
- D^2 be the mass balance coefficients on fish within the processing factory,
- A^1 be the mass balance coefficients governing transformation of raw fish into finished product,
- A^2 be the mass balance coefficients governing transformation of raw fish into finished product,
- $\boldsymbol{b}^1$ be the capacity of each trawler,
- $\boldsymbol{b}^2$ be the capacity of inventory storage limits of raw materials, and
- $\boldsymbol{b}^3$ be the capacity the finish products.

The decision variables are defined below. Let

- $\boldsymbol{w}$ be the binary variables indicating whether a trawler takes a given trip,
- $\boldsymbol{f}$ be the raw fish inventory, indicating the current quantity of each type of raw fish in each period, and
- $\boldsymbol{x}$ be the fish processing variables, indicating that a given type of raw fish is converted into a given product.

The IFPM model has the objective to

$$\text{maximise } \boldsymbol{c}^1\boldsymbol{w} + \boldsymbol{c}^2\boldsymbol{f} + \boldsymbol{c}^3\boldsymbol{x} \tag{1}$$

$$\text{subject to} \quad A^0\boldsymbol{w} + \boldsymbol{f} = \boldsymbol{0} \tag{2}$$

$$D^1\boldsymbol{w} = \boldsymbol{b}^1 \tag{3}$$

$$D^2\boldsymbol{w} = \boldsymbol{b}^2 \tag{4}$$

$$A^1\boldsymbol{f} + A^2\boldsymbol{x} = \boldsymbol{b}^0 \tag{5}$$

$$\boldsymbol{w} \in \{0,1\} \tag{6}$$

$$\boldsymbol{f}, \boldsymbol{x} \geq \boldsymbol{0}. \tag{7}$$

Constraint set (2) represents the relationship of the trawler scheduling variables $\boldsymbol{w}$ to landed fish $\boldsymbol{f}$, as a mass balance in movement of fish from trawlers to the factory. Constraint set (3) expresses the constraints involving only trawler scheduling, indicating, for example, that a trawler may be in only one place at a time. Constraint set (4) expresses fish processing constraints, modelling the flow of fish through the factory as raw fish is processed into various products. Constraint set (5) represents the mass balance constraints, representing the flow of raw, landed fish into the fish processing factory.

4.1 Generation of test problems

Let IFPM for a t-period (days) planning time horizon be denoted as IFPM(t). Three additional different test problems are introduced. These test problems are referred to as IFPMS(t) (*IFPM Small*), IFPML(t) (*IFPM Large*) and IFPMXL(t) (*IFPM Extra Large*) were generated by modifying the IFPM data for t-period planning time horizons. The IFPMS is smaller than the original problem. It has fewer trawlers and quality types. The IFPML is larger than the original problem. It has a larger number of trawlers and stock areas. IFPMXL has a larger number of trawlers and stock areas than the other problems. A summary of these problems for the IFPM is given in the Table 1 for a 30 day planning horizon.

Characteristics	IFPM(30)	IFPMS(30)	IFPML(30)	IFPMXL(30)
Number of trawlers	3	2	4	6
Number of factories	1	1	1	1
Number of species	8	8	8	8
Number of stock areas	2	2	3	4
Number of quality types	3	2	3	3
Number of product types	3	4	3	3
Number of constraints	10 885	6 550	15 456	24 404
Number of continuous variables	9 685	5 875	11 533	12 981
Number of integer variables	2 556	1 728	5 124	7 620

Table 1: *A summary of the characteristics of four different problem instances. Each runs over a 30 day planning horizon.*

5 A safety stock approach to deal with uncertainties

Many factors influence the scheduling of fishing trawlers and processing at an integrated fishery. These factors include catch capacity, variation in catch rate, weather and processing capacity. In planning fishing trawler scheduling, catch quota, processing and labour allocation, the manager of an integrated fishery takes into account the impact of the uncertainties of these factors. The manager plans production for a number of periods and implements the solution. Then production is planned for another planning horizon to make the next decision. In this way, the new problems are solved, and the new decisions are implemented in fragments for the true horizon of the fishery. Unless specially constrained, deterministic models leave zero end-inventory of raw materials. If there is no raw material in inventory, the processing plant must stay idle until the next landing of fish. For this reason, the optimal solution of a short-term model may not be an optimal solution of the fishery planning in the long run. This is known as end-of-planning-horizon effects (Hasan 2008). Decision errors occur when a shorter model horizon is used instead of the true horizon. The normal planning horizon for the fishery is one year. To overcome the difficulty of catch and demand forecasts for a long time horizon, managers use a shorter planning horizon. The differences between the long term and the short term planning horizon results in decisions errors.

In the following section, a series of experiments is described to deal with the end-of-planning-horizon effects by a safety stock approach and rolling horizon plans to investigate the effect of variation of catch rate on profit.

5.1 Setting inventory naively

Before starting the safety stock approach, some experiments were performed by setting the initial inventory level naively to observe the effects of the inventory of raw materials on the profit. If the beginning inventory level of raw material is naively set, the deterministic model yields lower or higher profit depending on the initial inventory level of raw materials. The naively set inventory level is performed, as this is how the fishery managers perform the task in the absence of optimization.

It might be expected that higher starting inventory levels raises profit, because the fishery gets raw materials for free, without having to catch it, but higher safety stocks do not necessarily ensure higher profit. From the experiments, it follows that IFPM(10) with a zero initial inventory level yields a profit of US$914 129. It is observed that the first two days there were no activities in the processing plant, because the fishery gets the first landings on day 3. Since there was no initial inventory of fish, the processing plant had to stay idle in the first two days.

IFPM(10) with some naively set beginning inventory level of raw materials at 25 950 kilograms yields a profit of US$935 265. The fishery uses little labour during period 1 to process this small amount of inventory of raw materials, but it uses higher labour during period 3, since the first landings arrive during period 3. The fishery experienced a lot of idle hours during the first two days. The deterministic model used 1 638 hours as regular labour, and for each period from period 3 onwards, it uses a different amount of overtime for each period. We also observe that during periods 3, 5, 7, and 9, the fishery achieves 2 landings each, resulting in higher overtime during these periods as shown in Figure 1.

With 50 100 kg as initial inventory, the profit becomes US$959 028. With initial inventory level at maximum storage capacity, the model yields a higher profit of US$1 034 318, but this is not the optimal solution for the 10-period model. If the maximum storage capacity is set as initial inventory level, the model uses regular labour for processing these inventory levels of raw materials during the first two days when there is no landings, but later on in planning time horizon there is idle time.

Starting with zero initial inventory level and increasing the level of inventory at each period up to the maximum storage capacity, it is observed that the higher the inventory level the higher the profit. One might expect from thes preliminarye experiments that higher initial inventory level results in higher profit.

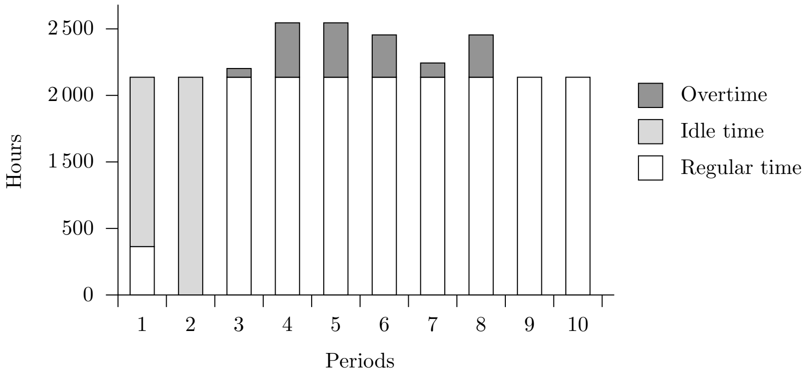

Figure 1: *Comparison of total time, regular time, overtime and idle time that occurs in a 10-period model solution with naively set initial inventory level of raw materials at 25 950 kg, which yielded a profit of US$935 265.*

5.2 Safety stock approach

A simple safety stock method is proposed for managing inventory to deal with end-of-planning-horizon effect due to variability in catch rate and also due to man-made variability in trawler scheduling. Therefore, a constraint is introduced which ensures that the beginning inventory levels of raw materials equals the final inventory level. In real life, the fishery needs initial and final inventories. At the beginning of a planning horizon, the trawlers need at least two days for fishing and landing their catch. If there is no initial inventory, there will be no activities in the processing plant and all labour will be idle during these two periods. Again at the end of a planning horizon, if there is no final inventory then the next planning horizon will face the same problem. On the other hand, if the fishery gets too much initial inventory, there will be no trawler scheduling for fishing. The fishery needs an appropriate level of initial and final inventory as safety stock.

The constraint takes the following form

$$z_{i,\ell,0} = z_{i,\ell,T} \qquad \text{for all } i \text{ and } j\text{, and} \tag{8}$$

$$z_{i,\ell,T} < 15\,000 \qquad \text{for all } i \text{ and } j, \tag{9}$$

where $z_{i,\ell,T}$ is the kilograms of fish species i of quality ℓ kept in inventory at the end of planning horizon t. The model determine how much raw material will be kept as inventory at the end of each period as safety stock. This type of safety stock creates a buffer against variability created by the trawler schedule (man-made variability), and the uncertainties of catch rate due to seasonality in the fish stock and weather conditions. From the analysis of the following section, it becomes clear that this safety stock balances the inventory holding cost, the idle time and overtime.

5.2.1 Comparison of a 10-day vs 30-day planning horizon

In this section a comparison of the results for a month (divided in three 10-day planning horizons) vs a single 30-day planning horizon is supplied. The first IFPM(10) is solved and yields a total profit of US$1 065 775. It uses 1 459 hours of regular labour per period.

The quota is reduced by the amount of fish caught during this horizon but allow the model to decide on the amount of regular labour to be used per period. The initial quota obtained is also fixed from the first 10-day model. The 2nd and 3rd IFPM(10) uses 901 hours and 786 hours of regular labour per period with no idle hours and yields total profits of US\$636 262 and US\$481 318, respectively. The total profit from these three IFPM(10) models is US\$2 183 355 where as a direct IFPM(30) yields a total profit of US\$2 300 871. Note that the three 10-day models use 12, 11 and 9 trips respectively which in total are 32 trips. A direct 30-day model use 35 trips. Results are shown in Table 2. Similarly, the same experiment is performed with two 15-day models one after another and observe that the 2nd 15-day horizon model yields lower profit and produces idle time. From these experiments it is clear that the quota allocation is important. The effect of smooth quota allocation on the profit is considered in the following experiment.

In this experiment, one-third of the total available quota was allocated for the 30-day horizon to each of the three 10-day horizons. Each 10-day model yielded a profit of US\$744 007. Thus three of these planning horizons yielded an average profit of US\$74 400 per period which is close to the average profit of a direct 30-day model (US\$76 696 per day). The total profit from these three 10-day models is US\$2 232 021 which is the closest to the 30-day profit (US\$2 300 871), resulting in a reduction of 2.9%.

It seems that the fishery can reduce the solution gap by smoothing allocation of available fish quota with a safety stock approach.

Planning horizon	Profit (US\$)	Number of trawler trips	Kilograms of fish landed
1st 10-day	1 065 775	12	573 705
2nd 10-day	636 262	11	451 440
3rd 10-day	481 318	9	320 512
Total of three 10-day	2 183 355	32	1 354 657
30-day	2 300 871	35	1 530 540

Table 2: *Comparison between three 10-day horizons and a 30-day horizon.*

5.2.2 A 10-day model example

The IFPM(10) is solved and yields a profit of US\$1 065 775, which is higher than all solutions in §5.1. It is observed that the solution has an inventory level of 104 481 kg raw materials at the beginning and end of the planning horizon. The results are shown in Figure 2.

Figure 2 also shows that the inventory level of raw material varies throughout the planning horizon, but the levels of each species are equal at the beginning and the end of the planning horizon. It seems that the initial inventory level is too high, but if it is considered that the capacity of a trawler is 85 000 kilograms and the inventory storage capacity of the fishery is 150 000 kilograms, it is not too high. If one or two trawlers land their catch during the last day (tenth day in the example), then the inventory level which the model optimizes does not seem too high. Note that the processing firm can process around 70 000 kilograms of fish every day. To handle the variability in catch rate and man made variability in trawler

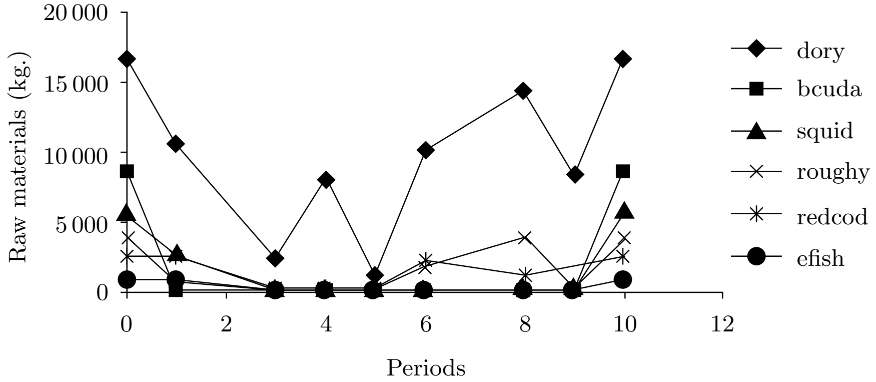

Figure 2: *Inventory levels of each species in different periods.*

scheduling, the fishery must have inventory of about two days' raw materials as safety stock.

In the example of the original problem, the IFPM(10) model yielded 104 481 kilograms of initial and final inventory and on the 10^{th} day, three trawlers landed with total landings of 140 085 kilograms. It is also observed that IFPM solved over 5 periods yielded 103 456 kilograms of initial and final inventory, and again three trawlers landed during the 5^{th} period with a total landing of 140 085 kilograms.

Thus, the model found an optimal safety stock level that is approximately equal to the processing capacity of two days. Figure 3 shows the inventory levels of raw materials and the number of landings in the final period for different planning horizons. The results from the model indicate that the inventory storage capacity of the fishery is 150 000 kilograms and the total capacity of the three trawlers is 155 000 kilograms. On the final day of each planning horizon, the fishery received three landings.

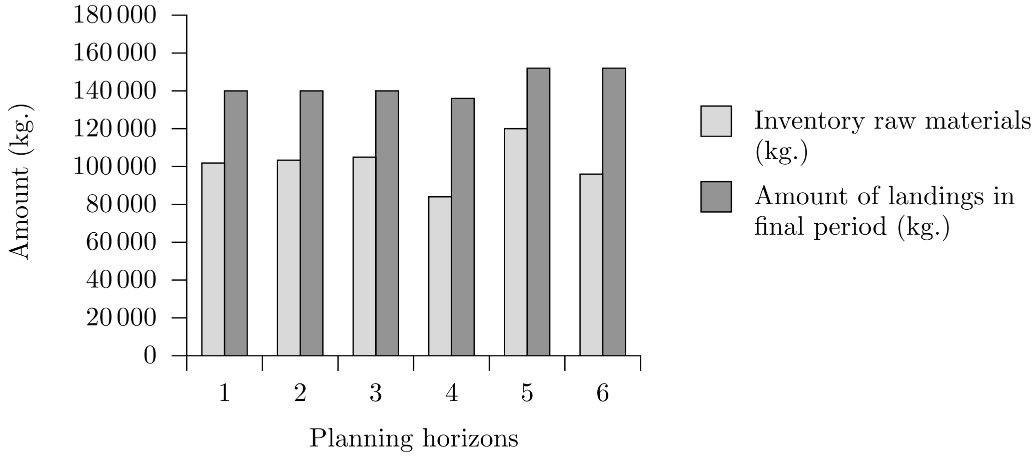

Figure 3: *Comparison of final inventory levels with the kilograms of raw materials landed during the final periods of 5, 10, 15, 20, 25, and 30-period planning horizons of IFPM*

In Table 3 it is illustrated that IFPM(10) balances inventory holding cost to other costs, and uses no overtime and no idle time. However, for some planning horizons IFPM uses overtime. For example, IFPM(20) yields 127 hours of overtime; IFPM(25) yields 537 hours of overtime; and IFPM(30) yields 172 hours of overtime. The number of overtime hours does not increase monotonically with the increase of planning horizon. The number of overtime hours used seems to depend on the length of the planning horizon, trawler landings, amount of raw materials available in different periods, and the amount of regular and idle hours. The question is why a deterministic model uses overtime? Table 3 shows that IFPM(25) uses 1 079 hours of regular labour per period. During the 5^{th} and 9^{th} period, the fishery gets three landings each with 153 450 kilograms of raw materials at each landing. To process these huge landings of raw materials, the model uses 269 hours of overtime labour on each of these two periods.

Length of planning horizon (days)	Regular labour per period (hours)	Total overtime (hours)
10	1 459	0
15	1 398	0
20	1 189	127
25	1 079	537
30	1 035	172

Table 3: *Regular labour and overtime labour used per period for different planning horizons.*

5.3 A comparison of safety stock and naively setting inventory

From §5.2 it is clear that the safety stock approach yielded a total profit of US$1 065 775 for IFPM(10), which is higher than any profit obtained using naively set inventory levels in §5.1, as shown in Table 4. The IFPM(10) determined a starting inventory level of 104 481 kilograms of raw materials.

Initial inventory	Profit (US$)	Regular labour (hours)	Overtime (hours)	Idle labour (hours)
0	914 129	1 705	1 479	3 410
25 950	935 265	1 638	1 616	2 910
50,100	959 028	1 501	1 330	1 781
150 000	1 034 318	1 371	1 382	429
Safety stock approach	1 065 775	1 459	0	0

Table 4: *Comparison of the effect of beginning inventory on profit and labour.*

By comparing the safety stock approach and naively set inventory levels, two conclusions may be drawn. A deterministic model may use some overtime. For the safety stock approach, a small amount of overtime is used, while with naively set inventory levels more overtime and idle time is used. The safety stock approach results in a higher profit than that of the naively set inventory level. Naively setting the initial inventory level is either insufficient for processing, or too much for processing during the periods when there is no landings. If too much inventory is available, the fishery uses more labour for processing the inventory; as a result in the later part of the planning time horizon, the fishery experiences a lot of idle time. The model optimizes the profit by setting the safety stock according to the requirement of the fishery. From Table 5 it may be seen that the initial inventories of the three different problem instances for different planning time horizons are lower than the storage capacity, landings in the final period, and trawler capacity.

Problem instance	Planning horizon	Total kg of initial inventory	Number of landings on the final period	Kilograms landed in the final period
IFPMS(t)	5	59 291	2	81 642
	10	65 418	2	101 852
	15	67 088	2	81 642
	20	68 926	2	81 642
	25	87 713	2	113 752
	30	77 041	1	52 890
IFPML(t)	5	150 000	4	230 870
	10	141 826	4	224 235
	15	150 000	4	237 600
	20	139 833	4	191 070
	25	142 377	4	214 335
	30	133 847	3	179 685
IFPMXL(t)	5	150 000	5	209 385
	10	150 000	5	241 313
	15	150 000	2	154 935
	20	150 000	4	214 335
	25	144 46	3	189 585
	30	133 670	3	179 685

Table 5: *Comparison of the total kg of raw materials landed in the final period for different total initial inventory levels for IFPMS(t), IFPML(t), and IFPMXL(t). The total trawler capacities are 120 000, 240 000 and 360 000 for IFPMS, IFPML and IFPMXL, respectively.*

6 Dealing with variability in the catch rate

Catch rate is the most important parameter influencing the trawler schedule and processing. The catch rate depends on weather conditions, season of the year, fishing area *etc.* Weather condition are neglected since the trawlers are able to fish in most weather conditions. Considering the last twenty years' catch rates (Clement 2004), as well as the catch data provided by the fishery, the average expected catch for IFPM is considered.

In this section the impact of variability of catch rate on the total profit of the fishery is investigated. A catch rate using two probability distributions are generated by means of a normal distribution and a lognormal distribution.

6.1 Catch rate generation with a normal distribution

A normal distribution is used to observe the effect of catch variability on the profit. Five different coefficients of variation from 10% to 50% in increments of 10% were used to generated five groups of catch rate parameters by means of

$$E_{a,i,t,v} = \max\{0, N(\overline{E}_{a,i,t,v}, CV \times \overline{E}_{a,i,t,v})\},$$

where $E_{a,i,t,v}$ is the expected catch per period t for vessel v of species i from stock a, while $\overline{E}_{a,i,t,v}$ is the average expected catch per period t for vessel v of species i from stock a and CV is the coefficient of variation.

For each coefficient of variation, the model was executed 10 times, delivering the average profit. The results are shown in Table 6. The percentage change in profit is the difference from the deterministic model solution expressed as a percentage of the deterministic solution. The average loss in profit for these five groups of catch rate is only 0.2%. The range of the percentage profit change is −0.42% to 0.03%.

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number			Profit in US$×$10^5$		
1	10.73	10.77	10.81	10.85	10.84
2	10.64	10.55	10.95	10.73	10.16
3	10.58	10.86	10.68	10.68	11.10
4	10.70	10.75	10.62	10.71	10.90
5	10.77	10.71	10.85	10.51	10.21
6	10.65	10.67	10.42	10.68	10.72
7	10.51	10.57	10.46	10.62	10.51
8	10.72	10.57	10.73	10.37	10.70
9	10.66	10.43	10.51	10.65	10.41
10	10.63	10.60	10.37	10.46	10.58
Average over 10 runs	10.66	10.65	10.64	10.62	10.61
% profit change	0.03%	−0.09%	−0.17%	−0.32%	−0.42%

Table 6: *Profit from random catch and variable trawler schedule for IFPM.*

The same experiment was conducted wit IFPMS, IFPML, and IFPMXL. The results are shown in Tables 7–9. Table 7 shows that the average loss in profit of IFPMS for the five groups of catch rate is only 0.7%. The range of the percentage profit change is −1.1% to 1.8%. Table 8 shows that the average loss in profit of IFPML for the five groups of catch rate is only 1.67%. The range of the percentage profit change is −2.61% to 0.48%. Table 9 shows that the average loss in profit of IFPMXL for the five groups of catch rate is only 0.014%. The range of the percentage profit change is −0.3% to 0.43%.

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number			Profit in US$×$10^5$		
1	7.084	7.223	7.292	6.906	7.065
2	7.077	7.019	7.272	7.013	7.516
3	7.111	7.045	7.215	7.000	7.182
4	7.094	7.221	6.978	7.215	6.815
5	7.011	7.278	7.188	7.069	7.387
6	7.176	7.006	7.034	7.104	6.978
7	7.108	7.164	7.247	6.905	7.315
8	7.170	7.355	6.890	7.130	6.710
9	7.177	6.971	7.194	7.074	6.712
10	7.014	7.042	7.104	6.792	7.209
Average over 10 runs	7.102	7.132	7.141	7.0201	7.089
% profit change	1.30%	1.70%	1.80%	−0.20%	−1.10%

Table 7: *Profit from random catch and variable trawler schedule for IFPMS.*

The results indicate three to four different types of trawler schedules for each coefficient

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$×$10^5$				
1	1.355	1.358	1.373	1.359	1.394
2	1.359	1.369	1.383	1.377	1.422
3	1.363	1.369	1.389	1.395	1.396
4	1.355	1.371	1.356	1.404	1.424
5	1.365	1.365	1.365	1.406	1.383
6	1.354	1.389	1.373	1.353	1.328
7	1.366	1.343	1.388	1.383	1.387
8	1.354	1.382	1.359	1.400	1.382
9	1.363	1.365	1.386	1.392	1.383
10	1.362	1.379	1.406	1.384	1.394
Average over 10 runs	1.360	1.369	1.378	1.385	1.389
% profit change	−0.48%	−1.17%	−1.79%	−2.33%	−2.61%

Table 8: *Profit from random catch and variable trawler schedule for IFPML.*

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$×$10^5$				
1	1.553	1.546	1.550	1.541	1.568
2	1.548	1.547	1.551	1.558	1.561
3	1.548	1.55	1.558	1.558	1.551
4	1.547	1.549	1.563	1.562	1.563
5	1.547	1.547	1.565	1.553	1.561
6	1.551	1.556	1.571	1.55	1.561
7	1.550	1.556	1.564	1.553	1.569
8	1.544	1.552	1.552	1.579	1.551
9	1.543	1.541	1.556	1.553	1.543
10	1.542	1.550	1.553	1.546	1.560
Average over 10 runs	1.547	1.549	1.558	1.555	1.559
% profit change	0.43%	0.29%	−0.27%	−0.08%	−0.30%

Table 9: *Profit from random catch and variable trawler schedule for IFPMXL.*

of variation. But the total number of trips for all cases remains the same (12 trips). For example, trawler 1 with a coefficient of variation of 10% lands its catch on period 3, 6, 8, 10 (required periods for each trips 3, 3, 2, 2 respectively) in one run and 3, 5, 7, 10 (required periods for each trips 3, 2, 2, 3 respectively) in another run. So the production schedule is changed accordingly. As a result, there exists little change in the total profit.

From the experiments of all four problem instances, the variability in catch rate has a little influence on the profit of the fishery. This is because the amount of landed fish of a trawler is the sum of several days' different catch rate. The catch rate fluctuation tends to be smoothed out. Also, the safety stock helps the fishery to use the inventory smoothly. To observe the effect of variability of catch rate on the profit in more detail, more experiments are conducted by fixing the deterministic trawler scheduling and allowing random catch in the following section.

6.2 Fixed trawler schedule and random catch

IFPM(10) was solved ranging the coefficient of variation for the catch rate from 10% to 50% in intervals of 10%. The model is solved 10 times and the average profit calculated.

The trawler schedule was fixed and the catch rate randomised. The results are shown in Tables 10 and 11.

The percentage change in profit is calculated as the difference between variable trawler schedule profit and fixed trawler schedule profit devided by the variable trawler schedule profit. The average loss in profit compared to the deterministic IFPM solution is only 0.8%, while the average loss in profit for the variable trawler schedule is only 0.6%.

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$\times10^5$				
1	10.6	10.77	10.81	10.85	10.84
2	10.64	10.52	10.94	10.75	10.15
3	10.52	10.69	10.47	10.68	10.98
4	10.66	10.75	10.59	10.57	10.67
5	10.76	10.58	10.75	10.44	10.19
6	10.65	10.64	10.42	10.46	10.59
7	10.5	10.47	10.46	10.44	10.38
8	10.65	10.55	10.73	10.32	10.5
9	10.66	10.43	10.51	10.6	10.4
10	10.56	10.47	10.31	10.42	10.58
Average of 10 runs	10.62	10.59	10.6	10.55	10.53
Change in profit compared to the variable schedule	−0.39%	−0.57%	−0.38%	−0.70%	−0.80%
Change in profit compared to the deterministic solution	−0.35%	−0.66%	−0.55%	−1.02%	−1.22%

Table 10: *The profit for IFPM if a fixed schedule and random catch is used to solve the model.*

Table 11 shows the change in profit of a fixed trawler schedule as opposed to free trawler schedules for 10 runs for each coefficient of variation. The total profit decreases by 0.4%, 0.6%, 0.4%, 0.7% and 0.8%, respectively, for different coefficients of variation. The average loss in profit is 0.58%.

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$\times10^5$				
1	1.30%	0.00%	0.00%	0.00%	0.00%
2	0.00%	0.30%	0.10%	0.10%	0.10%
3	0.60%	1.50%	2.00%	0.00%	1.10%
4	0.40%	0.00%	0.30%	1.20%	2.10%
5	0.10%	1.30%	0.90%	0.70%	0.20%
6	0.00%	0.30%	0.00%	2.00%	1.20%
7	0.10%	0.90%	0.00%	1.70%	1.20%
8	0.70%	0.20%	0.00%	0.50%	1.90%
9	0.00%	0.00%	0.00%	0.60%	0.10%
10	0.70%	1.30%	0.50%	0.40%	0.00%
Average loss in profit	0.40%	0.60%	0.40%	0.70%	0.80%

Table 11: *Percentage loss in profit when using a fixed trawler schedule as opposed to a variable trawler schedule.*

6.3 Fixed trawler schedule & random catch with **IFPMS**(10), **IFPML**(10), and **IFPMXL**(10)

IFPMS(10), IFPML(10) and IFPMXL(10) was solved for a fixed trawler schedule and the results compared to a random catch rate. The coefficient of variation for the catch rate was also ranged from 10% to 50% and for each coefficients of variation. The models was solved 10 times and the average profit was reported. The results are shown in Tables 12–14.

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$$\times 10^5$				
1	7.066	6.95	7.018	7.243	6.907
2	7.026	7.024	6.812	7.255	7.139
3	6.937	7.011	7.103	6.699	6.965
4	7.102	6.954	6.788	7.077	6.807
5	6.937	6.668	6.77	7.155	6.73
6	7.01	7.018	6.908	7.189	7.073
7	7.038	7.027	7.19	6.783	6.877
8	7.049	7.124	6.711	7.069	7.108
9	7.069	6.822	7.035	6.915	6.737
10	6.959	7.227	7.356	7.259	6.895
Average of 10 runs	7.0193	6.9825	6.9691	7.0644	6.9238
Change in profit compared to the variable schedule	1.16%	2.10%	2.41%	−0.62%	2.32%
Change in profit compared to the deterministic solution	0.11%	−0.40%	−0.59%	−0.76%	−1.24%

Table 12: *Profit from fixed schedule and random catch.*

Table 12 shows that the average loss in profit compared to the deterministic solutions of IFPMS(10) is 0.27% and compared to the variable trawler schedule solution it is 1.4%. Similarly, from Tables 13 and 14 the average loss in profit compared to the deterministic solutions of IFPML(10) is 0.56% and 1.25%, respectively, and compared to the variable trawler schedule solution it is 2.05% and 1.94%, respectively.

From these numerical experiments it is clear that the variability of catch affects the total profit only slightly. Since the total catch landed by a trawler is the sum of catches several periods (3 or 4 periods in the examples), the variability tends to smooth out over the whole planning horizon.

7 Catch rate generation with lognormal distribution

In the previous section a normal distribution was used for catch rate generation. In this section a lognormal distribution is used for generating the catch rates. The use of lognormal distribution is supported by Millar (1998). To implement this model in A Mathematical Programming Language (AMPL) (Fourer & Kernighan 1993), the standard deviation and the mean were derived from the standard deviation and mean of the lognormal distribution by by means of

$$\sigma_0 = \sqrt{\ln((CV)^2 + 1)} \quad \text{and} \quad \mu_0 = \frac{1}{2}\ln((CV^2) + 1) + \ln(\overline{E}_{a,i,t,v}).$$

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$\times 10^5$				
1	1.333	1.339	1.352	1.357	1.292
2	1.358	1.307	1.33	1.337	1.289
3	1.334	1.352	1.341	1.324	1.338
4	1.338	1.365	1.278	1.325	1.348
5	1.355	1.304	1.377	1.381	1.367
6	1.327	1.343	1.354	1.369	1.328
7	1.353	1.335	1.337	1.341	1.331
8	1.359	1.355	1.33	1.334	1.326
9	1.345	1.32	1.378	1.363	1.387
10	1.347	1.346	1.313	1.319	1.305
Average of 10 runs	1.3449	1.3366	1.339	1.345	1.3311
Change in profit compared to the variable schedule	1.08%	2.36%	2.81%	2.90%	4.18%
Change in profit compared to the deterministic solution	0.15%	0.77%	0.59%	0.14%	1.18%

Table 13: *Profit from fixed schedule and random catch of IFPML(t).*

As before, CV is the coefficient of variation and $\overline{E}_{a,i,t,v}$ is the expected average catch rate. Define the catch rate parameter as

$$E_{a,i,t,v} = \exp\left(N\left(\mu_0, \sigma_0\right)\right).$$

The standard deviation for the log normal distribution used in the model is expressed as a fraction of the mean of the distribution. The coefficient of variation is ranged for the catch rate at each stock simultaneously from 10% to 50% of the mean. For each coefficient of variation, the model was solved 10 times and the fluctuation in the profit is shown in Figure 4. The figure shows that the range of the fluctuation in the profit of the fishery is higher with the higher coefficient of variation.

A general decrease in the average profit may be noted as variability increases. The decrease in total profit, however, may not be monotonic as sampled catch rates with larger deviations from the mean may tend to cancel out their effects.

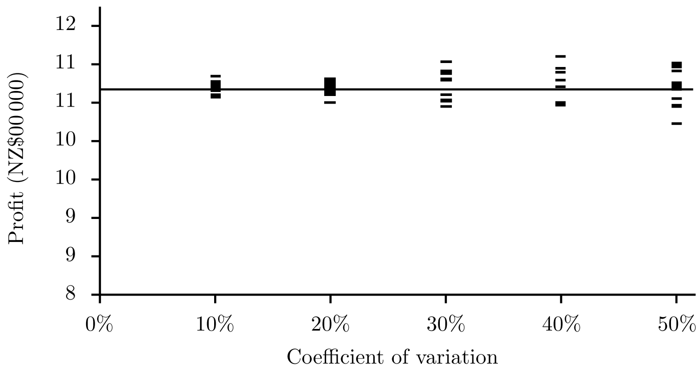

Figure 4: *Fluctuation in the profit due to variability in catch rate of IFPM.*

Coefficient of variation	0.1	0.2	0.3	0.4	0.5
Run number	Profit in US$$\times 10^5$				
1	1.54	1.541	1.519	1.535	1.5
2	1.545	1.514	1.521	1.519	1.457
3	1.556	1.534	1.49	1.488	1.429
4	1.543	1.545	1.527	1.545	1.544
5	1.546	1.549	1.53	1.52	1.541
6	1.542	1.524	1.531	1.505	1.517
7	1.541	1.538	1.517	1.532	1.498
8	1.535	1.544	1.512	1.502	1.501
9	1.547	1.52	1.508	1.53	1.518
10	1.531	1.53	1.534	1.536	1.507
Average of 10 runs	1.5426	1.5339	1.5189	1.5212	1.5012
Change in profit compared to the variable schedule	0.30%	1.00%	2.52%	2.19%	3.69%
Change in profit compared to the deterministic solution	0.02%	0.58%	1.56%	1.41%	2.70%

Table 14: *Profit from fixed schedule and random catch of IFPMXL(t).*

7.1 Random catch rates with IFPMS(10), IFPML(10) and IFPMXL(10)

Experiments with IFPMS(10), IFPML(10) and IFPMXL(10) were conducted varying the coefficient of variations for the catch rate at each stock simultaneously from 10% to 50%. For each coefficient of variation, each model was executed 10 times. Observe that the range of the fluctuation in the profit of the fishery is higher with the higher coefficient of variation.

7.2 Fixed trawler schedule and random catch

The same experiment as in §7.1 is repeated by fixing the trawler schedule obtained from IFPM(10) and allowing the catch rate to be random, ranging the CV for the catch rate from 10% to 50% in increments of 10%. For each CV the model is executed 10 times and the total profit recorded. Results are shown in Figure 5. It is clear that the fluctuation in the profit of 10 runs is higher with the higher CV. A greater decrease in the average profit is found as variability increases.

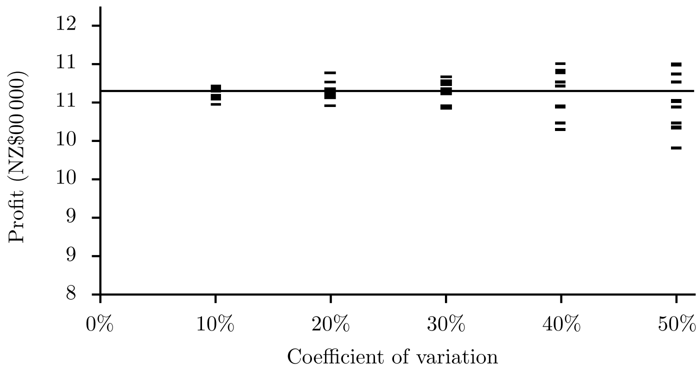

Figure 5: *Fluctuation in the profit due to variability in catch rate and fixed trawler scheduling of IFPM.*

8 Fixed trawler schedule and random catch rate with IFPMS(10), IFPML(10) and IFPMXL(10)

The same experimental setup as in the previous sections is repeated by fixing the trawler schedule obtained from the deterministic IFPMS(10), IFPML(10) and IFPMXL(10) and allowing the catch rate to be random. If the trawler schedule is fixed, the profits with different coefficients of variation are close to the deterministic solutions. The variability in catch rate does not affect the fishery considerably. It affects the profit of the fishery with between 0.01% and 2.0%. In the next section the effect of variation of catch rate by changing the mean catch rate is investigated.

In §6 and 7, the catch rate was large relative to the trawlers' capacity. Since the percentage change in profit was small in those sections, the high catch rate relative to trawler capacity may be contributing to the little change in the profit. In the following section the change in the mean is investigated, by varying the mean catch rate and observing its effect on the profit. The mean catch rate is set at 50%, then 66.6% of the mean and finally we create a representative data set with different rates in different periods along with zero catch rates due to very bad weather when it is impossible to fish.

8.1 Mean catch rate decreased by 50%

The mean catch rate is initially decreased by 50%. The IFPM(10) solved 10 times for each coefficient of variation. Since the mean catch rate is decreased, the total number of trawler trips is decreased by 1, resulting in the total profit to be reduced to US$837 167, an effective decrease of 21.4%. These experiments are performed with normal and lognormal distributions. The results are shown in Figure 6. The percentage profit losses for these coefficients of variations with normal distribution are shown in Table 14. The deterministic solutions are shown in dotted lines with coefficient of variation zero in the figures.

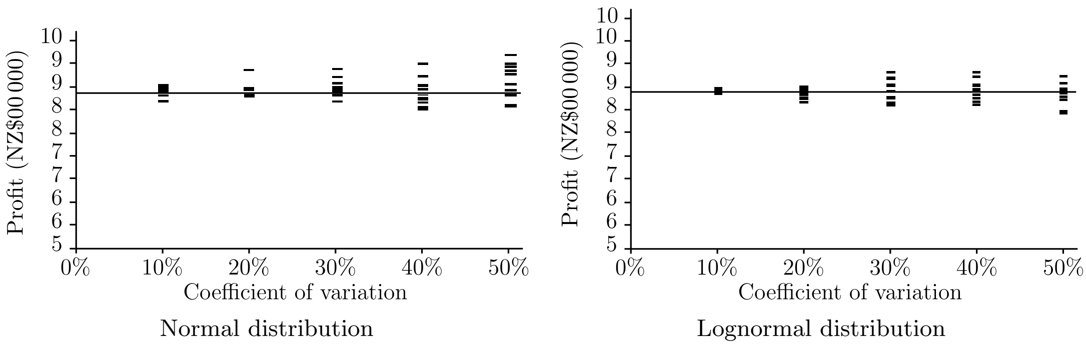

Figure 6: *Fluctuation in the profit of a 10-period model of IFPM due to variability in catch rate with the mean decreased by 50%.*

The same experiment is conducted with the different problems (IFPMS(10), IFPML(10), and IFPMXL(10)). From these experiments, the fluctuation in the profit of ten different runs of IFPMS(10) with a normal and lognormal distribution is very small. All the profits are very close to the optimal solution. The percentage profit loss for these coefficients of variations with normal and lognormal distributions are shown in Table 15. By fixing the deterministic trawler scheduling and allowing the catch rate to be random and allowing the processing variables to change, the experiments are performed with all four problem instances. The results of these experiments are similar *i.e.* all the profits were close to the optimal solution and the percentage profit losses for these coefficients of variations with normal distribution were very small.

8.2 Mean catch rate decreased by 66.6%

In this section the mean catch rate is decreased by 66.6% and IFPM(10) was solved 10 times for the same coefficient of variation as in the previous sections. The total number of trawler trips is decreased by 4. As a result the total profit of the deterministic model is reduced to \$668 134 resulting in a decrease of 37.3% in the average profit for the lognormal distribution. The results are shown in Figure 7. The percentage profit losses for these coefficients of variations with normal and lognormal distributions are shown in Table 15.

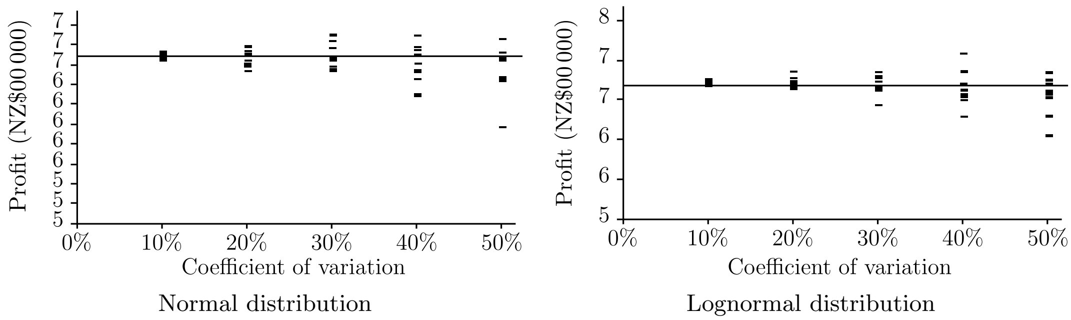

Figure 7: *Fluctuation in the profit of a 10-period model of IFPM due to variability in catch rate with the mean decreased by 66.6%. The deterministic solutions are shown in dotted lines.*

8.3 Different mean catch rates in different periods with some zero catch rates

The mean catch rate is investigated with different mean catch rates for different periods with some zero catch rates when the weather does not permit the trawlers to catch fish. The total number of trawler trips is decreased by 1. As a result the total profit of the deterministic model is reduced to \$902 666 resulting in a decrease of 5.9%. The results are shown in Figure 8. The percentage profit losses for the different coefficients of variations with normal and lognormal distributions are shown in Table 15.

All the experiments are performed with the three different problem instances IFPMS(10), IFPML(10) and IFPMXL(10). Similar results are obtained *i.e.* all the profits were close to the origional optimal solution.

9 Conclusion

A safety stock approach is proposed to model the end-of-planning-horizon-effects, and variability of the mean catch rate of an integrated commercial fishery. Safety stock is a

Criterion	Distribution	Problem	% change in the profit with different CV 0.1	0.2	0.3	0.4	0.5
Random catch and variable trawler scheduling	Normal	IFPM(10)	0.03	−0.09	−0.17	−0.32	−0.42
		IFPMS(10)	1.30	1.70	1.80	−0.20	−1.10
		IFPML(10)	−0.48	−1.17	−1.79	−2.33	−2.61
		IFPMXL(10)	0.43	0.29	−0.27	−0.08	−0.30
Random catch and fixed trawler scheduling (Compare to variable schedule)	Normal	IFPM(10)	−0.39	−0.57	−0.38	−0.70	−0.80
		IFPMS(10)	1.16	2.10	2.41	−0.62	−2.32
		IFPML(10)	1.08	2.36	2.81	2.90	3.18
		IFPMXL(10)	0.30	1.00	2.25	2.19	3.69
Random catch and fixed trawler scheduling (Compare to deterministic schedule)	Normal	IFPM(10)	−0.35	−0.66	−0.55	−1.02	−1.22
		IFPMS(10)	0.11	−0.40	−0.59	0.76	−1.24
		IFPML(10)	0.15	0.77	0.59	0.14	0.18
		IFPMXL(10)	0.02	0.58	1.56	1.41	2.70
Random catch and variable trawler scheduling	Lognormal	IFPM(10)	−0.31	−0.26	−0.74	−1.41	−0.02
		IFPMS(10)	−0.85	−1.39	−1.87	−2.15	−1.95
		IFPML(10)	−0.24	−0.70	−1.32	−0.92	−1.61
		IFPMXL(10)	−0.22	−0.36	−0.16	−0.34	−0.39
Random catch and fixed trawler scheduling (Compare to deterministic schedule)	Lognormal	IFPM(10)	0.32	0.26	0.08	0.74	1.39
		IFPMS(10)	−0.01	−0.58	0.70	0.05	−0.87
		IFPML(10)	−0.21	0.44	0.82	0.56	1.88
		IFPMXL(10)	0.39	0.21	2.31	1.21	2.46
50% decrease in mean	Normal	IFPM(10)	−0.12	−0.49	−1.32	−0.20	−3.29
		IFPMS(10)	−0.68	−0.06	−1.30	−2.20	−3.40
		IFPML(10)	0.14	−0.43	−0.28	−0.76	−1.52
		IFPMXL(10)	0.37	−0.32	−0.86	−1.07	−2.18
50% decrease in mean	Lognormal	IFPM(10)	−0.38	−0.17	−1.09	−0.99	−0.65
		IFPMS(10)	−0.46	−1.45	−1.97	−3.37	−2.69
		IFPML(10)	0.06	−0.57	−0.36	0.69	−0.43
		IFPMXL(10)	0.45	−0.42	−0.68	−1.22	−1.50
66.6% decrease in mean	Normal	IFPM(10)	0.2	0.3	−0.21	1.53	1.90
66.6% decrease in mean	Lognormal	IFPM(10)	−0.18	−0.13	−0.05	0.19	1.30
Different mean in different period	Normal	IFPM(10)	0.19	0.93	0.16	1.02	1.14
Different mean in different period	Lognormal	IFPM(10)	0.02	0.56	0.67	0.74	0.63

Table 15: *Summary of the percentage solution gap in different problems with different experiments.*

simple method to manage man-made variability, lumpy schedules and with end-effect-of-planning-time-horizon. Mean catch rates are generated by using normal and lognormal probability distributions. It is concluded from the experiments that more complicated stochastic integer program seems to be unnecessary, since the variability in catch rate of fish has a minor impact on profitability of the fishery. Using the average expected catch rate in a deterministic model appears to be effective.

Acknowledgements

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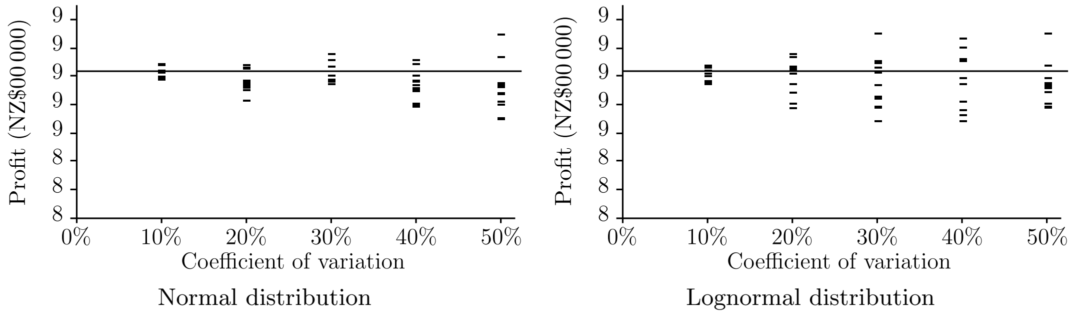

Figure 8: *Fluctuation in the profit of a 10-period model of IFPM due to variability in catch rate with different means in different periods. The deterministic solutions are shown in dotted lines.*

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