OPTIMIZATION OF DECENTRALIZED ADAPTIVE TRUCK DECISION RULES:

A SPATIAL DYNAMIC STOCHASTIC FOREST COMPANY PROBLEM[1]

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SUMMARY

A computational procedure is suggested which gives the optimal adaptive truck transport decision rules in a typical forest company problem. The adaptive truck scheduling problems and the raw material stock problems are economically and physically linked. In the same process, the different stocks obtain their optimal levels.

Assumptions:
- The timber harvest is spatially distributed and can not be perfectly predicted.
- If, during some period(s), there is no timber available at some mill(s), production has to stop and economic losses are considered.

The optimal "Reservation Cargo" and the optimal "Expected Marginal Revenue Slope" are determined in an example. These are the two optimized parameters of the adaptive decision function. It is found that the suggested method gives extremely robust estimates of the optimal values of these adaptive decision rule parameters.

Keywords: transport optimization, adaptive decisions, stock level, profit function, forest industry

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1. INTRODUCTION

The ambition of this paper is to try to answer the following questions:

- How should we define the typical forest industry roundwood transportation problem?
- How are the transport and stock level decisions linked?
- What relevant information is available and how is this changing over time?
- Is it possible to utilize the sequentially available stock state information and optimize adaptive decision rules?

We instantly realize that these questions are linked in several ways. First, we should be aware that models which have been easy to analyze with existing mathematical and numerical methods usually have been preferred to more complicated but perhaps more relevant models.

This has often meant that formulations where the objective function is a linear function of the decision variables (usually transported volumes from locations i to locations j) and the constraints are linear have been used. Compare the many examples in Wagner (1975). An application of such a model in a forest company timber transport problem is found in Berg and Larsson (1994). With linear programming based on standardized commercial computer codes, many decisions have been possible to handle simultaneously, which certainly has been practical. Usually, the assumptions of perfect information (and constant conditions over time) have implicitly been made, in order to motivate linear programming. Clearly, in an assumed world of constancy, there is no need for safety stocks. The flow can be optimized now and for ever and no disturbances will destroy the plans. Such a deterministic infinite horizon plan, including transport and processing, is calculated with standard linear programming by Eriksson and Björheden (1989).

Stock policy decisions have traditionally represented another area of analysis. Most courses on management and operations research include stock policy optimization and different versions of deterministic and stochastic optimization models. The links to transport optimization are usually neglected.

As expected, the principles of "just in time", JIT, management have grown out of this confusion. Clearly, it is easy to see that stocks imply costs. However, they usually also represent safety and cheaper transport alternatives. As the size of the raw material stock at the factory increases, the probability of production stops caused by disturbances in the transport system decreases. Egbelu and Wang (1989) and Fieten (1989) are discussing scheduling and integration of suppliers in JIT systems. Chyr et al. (1990), Ramesesh (1990) and Jones (1991) study JIT in connection to inventory and ordering models. Singh and Brar (1992) study JIT manufacturing systems and Cossens (1992) and Casper (1992) give inventory and truck scheduling perspectives on JIT. Fawcett and Birou (1993) and Johnson and Stice (1993) continue the analysis of JIT systems. Anon (1994) points out that the costs of JIT may be high.

The obvious economic insight is that the expected marginal revenue of the stocks should equal the expected marginal costs. If this is not true, the stock levels are too low or too high. However, it is much easier to calculate the expected marginal cost than the expected marginal revenue. The expected marginal revenue is a function of the marginal net profit in the production plant and the probabilities of different disturbances in the total transport and production system.

Such problems have not until the latest years been possible to handle numerically and certainly not with informative analytical models. Since we have integer decisions, nonlinearities and often stochastic phenomena in the systems, methods that can handle such problems are needed. Fundamental useful principles and methods are found in Wagner (1975). Some important examples of recent transport and stock level optimization papers and methodologically interesting forestry studies will be reported here:

Shen and Sessions (1989) contribute with a network programming model for log truck scheduling. Sessions and Yeap (1989) optimize road spacing and equipment. Bare, Briggs and Mendoza (1989) use soft optimization in log allocation and Sessions and Sessions (1992) discuss tools in tactical forestry planning. Koskosides et al. (1990 and 1992) suggest and apply a heuristic model for vehicle routing and scheduling. Masters (1993) optimizes stock levels in multi-echelon distribution inventories. Atkinson (1994) optimizes vehicle scheduling with heuristic methods and Eiderbrant, Forsen and Segner (1994) optimize the number of pulp wood trucks in a Swedish pulp mill company, taking stochastic spatially distributed harvests and other temporal variation into account. Weintraub et al. (1994) present a heuristic model for forest planning which can handle mixed integer formulations.

When we have stochastic systems, it is often important to take advantage of the information when it appears. Optimization of adaptive decisions is presently of interest in many fields. A report on recent adaptive optimization results in forestry is given by Lohmander (1994a). Optimal adaptive production and stock level decisions in forest companies are studied by Lohmander (1992) and (1993). Lohmander (1994b) investigates one version of a stochastic log transport problem within a forest company. That model has some conceptual connection to the model in this paper. That model, however, was not based on the moves made by individual trucks. It was designed on a more aggregate level. In this paper, a truck decision level model will be developed. One model similarity is that Lohmander (1994b) contained the EMRS, the expected marginal revenue slope, a concept which will be used also in the model of this paper.

The original idea of "just in time" should be questioned. "- Minimize the stocks and deliver as late as possible!" is the simple but usually not economically optimal recommendation of the "just in time believers". The critical reader who considers costs and revenues should realize that optimal stocks and transport patterns are linked and that economically optimal stock levels seldom are zero.

2. SUGGESTED ASSUMPTIONS AND MODEL

In this paper, these assumptions will be stated and used:

- The available stocks at road sides can not be perfectly predicted several weeks ahead. The deviation from the predictions of the amount of wood which becomes available at road sides every day is affected by errors in estimated forest stocks, local decisions, technical disturbances in harvesting machines, diseases affecting the labour force productivity, technical problems in terrain transport vehicles and weather conditions. The snow depth and the amount of water in swamps and in soils with clay may affect the efficiency of harvesting and terrain transport considerably. Snow and rain predictions usually contain very large errors, even when the horizons are shorter than a week.

- If, in some period(s), there is no timber (or pulp wood) available at some mill(s), production has to stop and this causes a considerable economic loss to the company. The amount lost is of course a function of the present product prices. Rapid changes in product prices and the effects on the optimal adaptive short run raw material flow was discussed by Lohmander (1994b).

- The companies keep safety stocks at the mills to make it less likely that production at the mills has to stop because of timber supply variation.

- The expected marginal revenue and the expected marginal cost of a safety stock should be the same if the stock level is optimal. Furthermore, the expected marginal revenue of a particular stock is a decreasing function of the size of that stock level.

- The different stock levels will continuously change up and down because of random changes in transport and production.

- The cost of a particular transport activity is not independent of the other transport activities. (Traditional LP formulations are hence often irrelevant!) This becomes obvious when we study individual trucks and their moves.

For instance, assume that A, B and C represent the corners of a triangle and that there are straight roads of the same quality connecting these corners. (Only these three locations exist in our problem.) Clearly, if the truck several times takes cargo from A to B and then some other cargo from B to C, it is obvious that it should go from C to A the same number of times (if it should not take some other cargo from C to B and/or from B to A on the way back.). Hence, the "cost" of transport activities from C to A is a function of the other transport activities. In other words, the traditional assumption that the costs of different transport activities are independent and should simply be added in a linear programming formulation is usually irrelevant.

3. SUGGESTED MODEL PROPERTIES

Hence, the author suggests that a relevant model should be able to analyze a problem with the following characteristics:

- Large number of periods.
- High spatial resolution.
- Stochastic spatially distributed harvests and adaptive transport decisions.
- The positions of the different trucks should continuously be considered.
- The cargo of every truck and the stocks at road sides and at the mills should continuously be considered.
- The economic consequences of lack of timber (or pulp wood) at the mills should be considered.

4. OPTIMIZATION METHOD

When we select the optimization method, we have to accept that the relevant problem has the following properties:

Road side stocks:
- are stochastic processes.
- are spatially distributed.
- change over time.

Truck moves:
- are often spatial.
- include loading and unloading.
- must be studied during a number of complete cycles.

Mill production and raw material stocks:
- must be studied during a large number of periods in order to estimate the probability and expected costs of production stops caused by lacking roundwood.

We make the following computational observations:

- The state space is multi dimensional (stocks and truck positions).
Usually, more than 100 dimensions are needed in order to represent the problem in sufficient detail.
- The state resolution needed is high.
- The number of periods is high. Usually, more than 100 periods are needed.

In principle, the problem could be stated as a stochastic dynamic programming problem. However, the very large number of state dimensions makes it impossible to use that method.

The author proposes the following method:

- A large number (> 1000) of stochastic full system multi period simulations with alternative adaptive control function parameter values are performed.
- The total profit (present value) is calculated in every simulation.
- The total profit (present value) is statistically estimated as a function of the adaptive control function parameters.
- The adaptive control function parameters are optimized via analytical derivations based on the statistically estimated total profit function.

Stochastic simulation will probably continue to be an area of importance, in particular in combination with optimization algorithms. Smith (1989) describes the increasing use of simulation and McClelland (1992) makes use of simulation in the solution of manufacturing problems.

5. THE ADAPTIVE CONTROL FUNCTION PARAMETERS

The model suggested and analyzed here is only one example out of an almost infinite number of possible models. The suggested model is sufficiently simple to be explained in some detail within this paper. A particular set of adaptive control rules suited for highly decentralized truck transport decisions is proposed.

As always, every restriction has an expected cost which may or may not be strictly positive. This follows from the famous "Le Chatellier principle".

In this context, we may say that we put a restriction on the adaptive decisions if we do not use (restrict ourselves from using) some of the available information.

Furthermore, we may restrict ourselves from using the available information in the most profitable way. This is what happens when we suggest a particular functional form of the adaptive control.

It is usually an open question if we should determine a particular transport volume according to a linear, a quadratic or a cubic function of an observed stock level. Perhaps the optimal transport volume in that specific direction is some particular multidimensional polynomial function of all stocks and truck positions in the region?

In this paper, we select an adaptive decision structure which is conceptually very simple. As a result, the principles can be explained and discussed in the text.

The adaptive control parameters to optimize within this paper are:

- The reservation cargo (RESC)
- The EMR slope (EMRS)

The reservation cargo, RESC, is an adaptive control parameter which has the following use in the decisions:

- When the cargo of a truck is lower than the reservation cargo:
    - Go to a forest road stock and load more.
    - When you select which place to go to:
        - Consider distance and stock volume.
- When the cargo of a truck is higher than the reservation cargo:
    - Go to one of the mills and unload.
    - If you find more along the road and have room for it; Load.
    - When you select which mill to go to;
      Consider the distance to and the stocks at the mills.
      (Calculate the expected marginal revenue, EMR, of the stocks at the different mills.)

The expected marginal revenue slope, EMRS, at the mill(s) is one adaptive control parameter. It is defined as the first derivative of the expected marginal revenue with respect to the raw material stock at the mill. The decisions concerning the timber transport directions are based on the EMR and the distance to the mill. The EMRS and the stock level are used to calculate the value of the EMR.

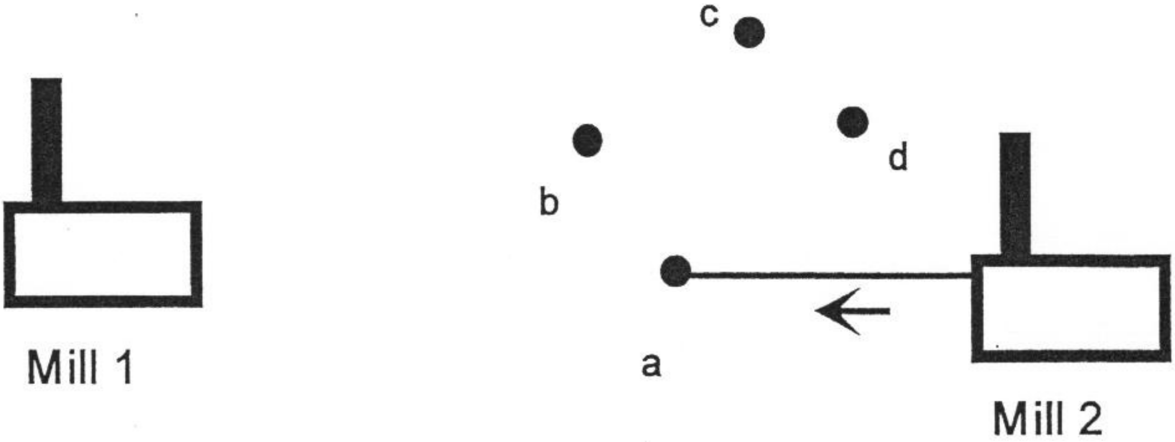

Figure 1. Illustration of the forest company, the two mills and some locations of forest road stocks. The first move of one of the trucks without cargo is to go from Mill 2 to forest road stock a. This decision is based on information concerning the cargo, the distances to different forest road stocks and the available volumes of stocks at those locations.

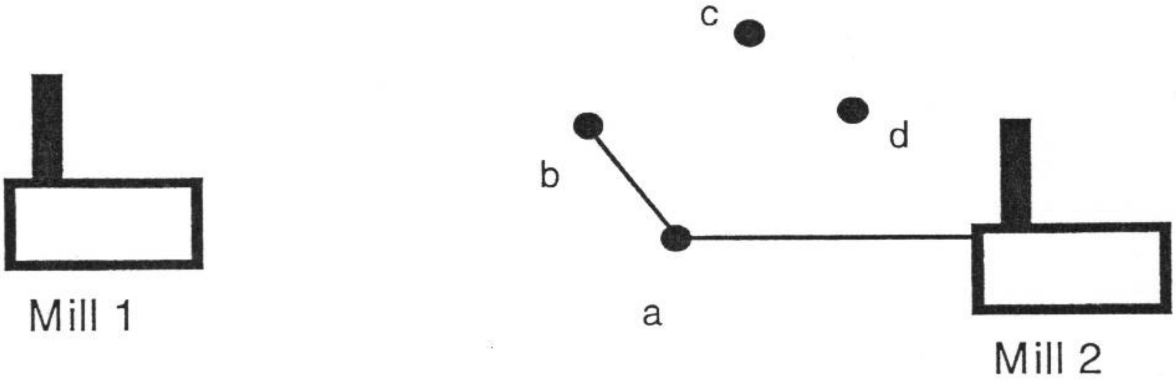

Figure 2. Since the cargo of the truck is not yet higher than the reservation cargo, the decision is to keep on going to different road stocks. Distances and available stock volumes are used in the selection decisions.

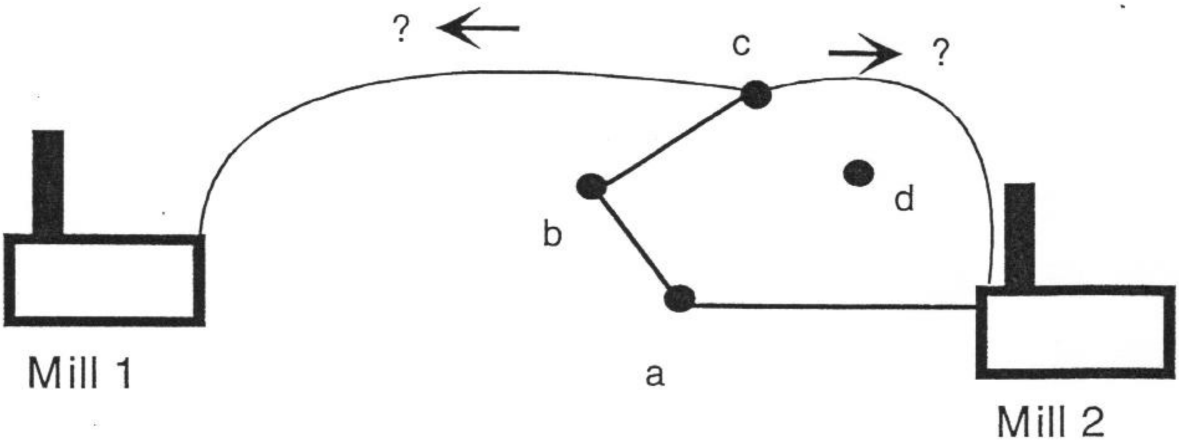

Figure 3. Now, the truck cargo exceeds the reservation cargo and the decision is to go to one of the mills and unload. The expected marginal revenue, EMR, of the stocks at the different mills and the distances to the mills from the truck are used in the selection. The values of EMR are based on the stock levels at the mills and the EMRS parameter, which is optimized in the model.

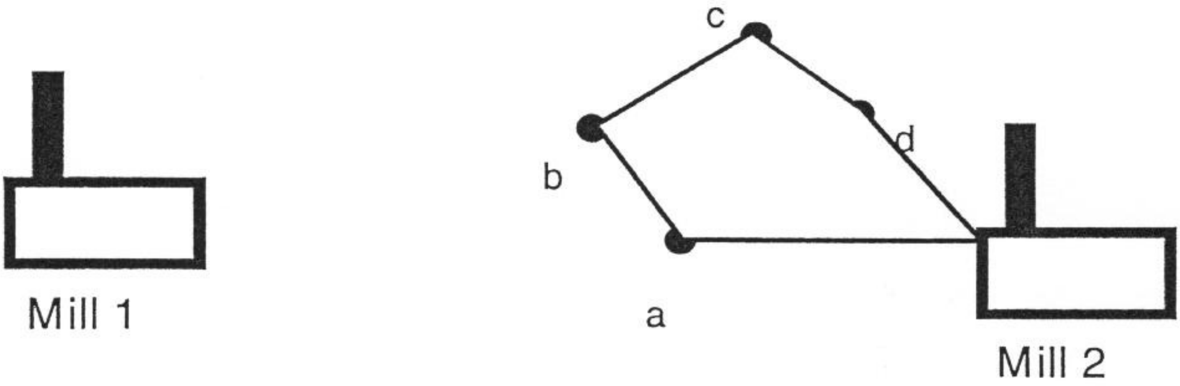

Figure 4. The adaptive decision was to go to Mill 2. Along the road, more pulp wood is found. Since there is some space left on the truck, this is loaded. Finally, the truck unloads at the mill and new adaptive decisions are taken.

6. THE OBJECTIVE FUNCTION ESTIMATED FROM SIMULATION RESULTS

After 1650 stochastic full system simulations with different adaptive control parameter values, a data set was created and used to estimate the total profit function, ¶. This is found to be:

$$\begin{array}{lllllll} \P = 5560 & + 190\,C & - 8.19\,CC & + 108\,S & - 9.69\,SS & + .252\,SSS \\ \quad (107) & (21.3) & (-21.5) & (14.5) & (-13.1) & (10.6) \\ & & & & & \\ \quad + 6.46\,SC & - .232\,SSC & & & & \\ \quad (11.6) & (-8.28) & & & & \end{array}$$

C denotes RESC, reservation cargo, and **S** denotes [(-1) * EMRS]. The t-values are given below the coefficients. We should observe that the estimated t-values have very high absolute values. The probabilities that the wrong signs of the parameters have been estimated are almost zero. The estimated function is illustrated in Figures 5 and 6.

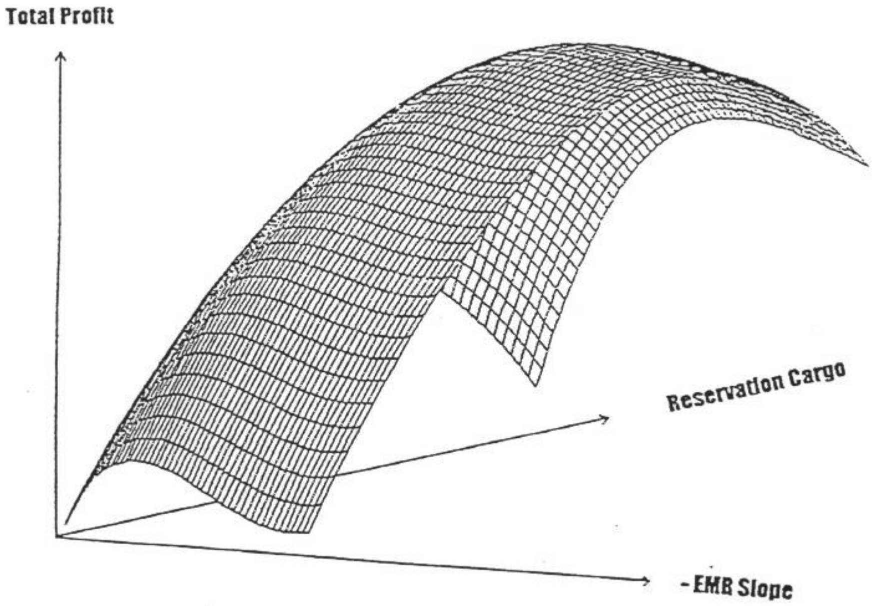

Figure 5. The total profit function in perspective a.

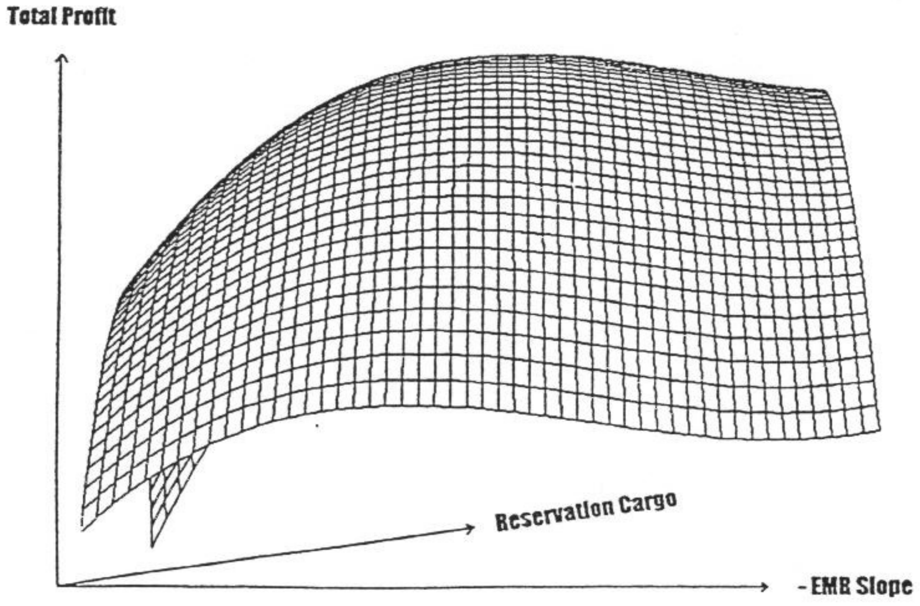

Figure 6. The total profit function in perspective b.

7. OPTIMIZATION OF THE ADAPTIVE CONTROL PARAMETERS VIA DERIVATIVES

The first order optimum conditions are:

(S = -1 * EMRS, C = RESC)

$$\frac{\delta \Pi}{\delta S} = 0$$
$$\frac{\delta \Pi}{\delta C} = 0$$

One solution to the optimum conditions is given by:

$$(S, C) = (11.64, 14.27)$$

The other solutions to the equation system can be rejected on logical grounds. It turns out that the obtained solution is "reasonable". No extrapolation of the estimated objective function outside the tested parameter range is needed.

The derived parameters have the expected signs. The value of the reservation cargo, RESC, is reasonable.

(CAP/2) < RESC < CAP, where CAP denotes the maximum cargo of a truck. Furthermore, a graphical analysis of the objective function shows that there is one unique maximum within the investigated parameter range. This is found in Figures 5 and 6.

Can we show that the obtained optimum is indeed a maximum without the graphs? The second order maximum conditions are satisfied. At the solution to the first order conditions, we find that:

$$|\Pi_{SS}| < 0$$

$$\begin{vmatrix} \Pi_{SS} & \Pi_{SC} \\ \Pi_{CS} & \Pi_{CC} \end{vmatrix} > 0$$

Hence, we conclude that the optimal reservation cargo, RESC, is 14.27 and EMRS, the "optimal slope" of the mill selection function EMR with respect to the raw material stock, is -11.64.

8. ILLUSTRATION OF ADAPTIVELY OPTIMIZED TRUCK MOVES

Will the optimized control parameters give understandable adaptive truck decisions in a full system simulation? This is a most important question which should be asked. In order to answer the question, we simulate the system with the optimized parameters.

In the Figures 7 to 9 we will follow the moves of the trucks and the development of the stocks during a number of periods. These Figures should be understood the following way:

Each Figure represents a geographical map in a particular time period. North is up and east is to the right. The periods are denoted by "Time" and found down to the left. There are 9 rows and 9 columns, 81 possible locations. There are two trucks found on every map. These look the following way: [X Y], where X is the truck number (1 or 2) and Y is the present cargo of the truck. The positions of these trucks change over time and in every period the trucks are found in some of the 81 locations. All other figures in the maps denote pulp wood stocks. If a truck is in the same location as a particular stock, the truck is found instantly below that stock on the map.

All stocks (except two) on the map denote forest road stocks. The two exceptions are the stocks of two different mills. These are found on the middle row. The stock of mill 1 is found in the left column and the stock of mill 2 is in the right column. It is sometimes convenient to denote the position of a particular stock by row and column in the following way: The stock of mill 1 is found in (5,1) and the stock of mill 2 is found in (5,9).

0	2	1	1	0	0	2	4	0
3	0	0	0	2	2	0	3	0
5	2	0	0	2	3	0	3	2
0	0 [217]	0	0	0	1	2	0	1
1	1	3	0	0	0	0	1	17
2	2	2	0	1	2	0	0	0
3	0	1	1	1	0	0	0 [1 4]	0
5	1	0	0	3	0	0	0	2
7	3	2	0	2	2	0	1	5

Time = 50

Figure 7. Map of the stocks and trucks at Time = 50. Explanations are given in the main text.

0	2	2	1	0	0	2	4	0
3	0	0	0	2	2	0	3	0
5	2	0	1	4	3	0	3	2
0	0	0	0	0	1	2	0	1
1	1 [217]	3	0	0	0	0	1	16
2	2	2	0	1	2	0	0	0
3	0	1	1	1	0	0	0	0
5	1	0	0	3	0	0	0 [1 4]	2
7	3	2	0	2	2	0	1	5

Time = 51

Figure 8. Map. Compare Figure 7.

2	2	4	6	0	0	2	4	0
3	0	0	0	2	2	0	3	0
0	2	0	1	6	3	2	3	2
[2 5]								
0	0	0	0	0	1	2	0	1
14	0	3	0	0	0	2	1	10
2	2	2	0	1	2	0	0	2
3	0	1	1	1	3	0	0	0
5	1	0	2	4	2	0	0	0
								[113]
7	3	5	0	2	2	0	0	0

Time = 57

Figure 9. Map. Compare Figure 7.

We may conclude that the simulated truck decisions seem reasonable in the illustrated example. This ends the investigation of the question:
" - Are the obtained adaptive control parameters reasonable?"

9. GENERAL CONCLUSIONS

The proposed optimization method makes it possible to handle the relevant problem with:

- a large number of state dimensions
- a large number of periods
- stochastic stock changes
- sequential information
- adaptive decisions

The author has not been able to find any alternative optimization method that makes it possible to handle the relevant problem.

The proposed optimization method gives a highly reliable estimate of the total profit (present value) function.

The final stages of the optimization of the adaptive control function parameters follow the standard (analytical) procedure from nonlinear optimization.

The solution can be shown to be a local maximum and the global maximum to the problem where all extrapolations are forbidden.

The option to use graphical stage by stage state maps makes it easy to study the structure of the model and the consequences of alternative adaptive control function parameters.

10. SUGGESTIONS FOR THE FUTURE

The model could be adapted to different forest companies. Perhaps other control function parameters should be optimized in those cases? The same general structure could probably be used.

Companies in other sectors with regionally distributed supply and demand could find applications of adapted versions of the model useful.

Many other kinds of adaptive problems could be solved with modified versions of the suggested and tested procedure.

In particular, the issues of optimal coordination and decentralization deserve attention.

It is possible to define a large number of alternative decentralized adaptive truck decision rules where the positions, cargo and latest moves of the other trucks are considered. Compare the adaptive decentralized decisions taken by individual birds during a flight in formation!

It should also be possible to define completely centralized adaptive decision rules where the central decisions are based on complete state information at a selected level of detail and resolution. This level could be optimized.

However, a higher level of coordination usually implies more complicated, expensive and slower decisions. Furthermore, the need for information processing and data transfer increases.

The optimal level of decentralization is in general an open question. Most likely, the optimal degree of coordination is not exactly the same in any companies. This has already been discovered by most actors in the industry and in the military all over the world. Furthermore, the kind of operation to be undertaken and other conditions of relevance strongly influence the optimal kind of leadership and control.

The approach and tools presented in this paper will hopefully make it easier to determine the optimal adaptive way of decision making in different situations.

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