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A Logistics Planning Model For An Arctic Pipeline

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INTRODUCTION

THE IMPORTANCE of logistics planning in large-scale business operations is well acknowledged. The complexity of the planning process, coupled with the fact that the cost of physical distribution and in-transit storage can range as high as 10% of total expenditures, provides ample opportunity for significant savings to those who address themselves to the problem in a systematic manner.[1] One such systematic approach to a large scale logistics problem is outlined in this paper.

The logistics problem is first described in general terms, a linear programming model is then developed as an aid to solving the problem, and finally the model's potential is demonstrated by giving a few examples of its application in the construction of a proposed arctic pipeline.

THE PROBLEM

It is required to move a number of commodities from many sources to several destinations over a specified planning period which can be sub-divided into a number of discrete time intervals (e.g., days, weeks, months, etc.). The quantity demanded by commodity and destination is known for each of these time intervals. Similarly, the quantity available and its associated cost is given for each commodity by source location and time interval. It is possible for a commodity to have a number of alternative sources which vary in location and number through time.

Several transport modes exist to move the various commodities, and rates on a "cost per unit" basis are available for each commodity. Furthermore, some or all of the transport modes may be subject to capacity restrictions because of limited resources of plant and equipment or perhaps due to seasonal weather factors (e.g., river barges in the winter freeze-up period). Goods can move multimodally where price or physical restrictions dictate such a routing. In these cases transshipment takes place, again at a cost applied to each unit of goods so transferred. If restrictions exist on the quantity of goods that can be transferred per time interval at any breakpoint, then such limits must be explicitly acknowledged (e.g., the capacity of a terminal facility per specified time interval).

In some instances it may be necessary to stockpile or warehouse goods during one or several of the specified time intervals. Each storage location so defined will have a "per period" capacity and a "per unit" storage cost associated with each commodity that can move through the facility.

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Given a logistics problem such as outlined above, one is interested in minimizing the cost of routing goods through time and space subject to the given restrictions, but other objectives are also important. Transportation equipment and auxiliary facility needs should be identified and quantified. Various types of sensitivity analysis should be possible as well. For example, one would like to be able to test quickly and thoroughly the effects of various rates and prices on the over-all solution.

It would also be advantageous to have an indication of return on potential investments in transportation plant and equipment, storage facilities, etc. Furthermore, it might be desirable to measure the "added" cost to certain large projects of fulfilling national or social goals if such goals were known or could be defined. Another objective might be to monitor and co-ordinate the various modal carriers involved in the operation or project. The following section develops a model, which can, in varying degrees of thoroughness, address itself to these and other goals associated with a logistics problem.

THE MODEL

Conceptually, the basic movements, activities and functions necessary to describe the logistics problem can be represented by flows over directed *arcs* in a network. Commodity movements, storage activities, supply functions, etc., can be represented in this manner. The *nodes* in the network represent the beginning or end of commodity shipments, transfers or storage activities. For example, a node could represent the end of a truck movement and the beginning of a transshipment activity which would place the commodity onto a river barge.

Restrictions on commodity supplies, transport plant and equipment, storage facilities, etc., are achieved by limiting the flow on all arcs involved in such functions. The capacity of a warehouse during a specific time interval can be restricted by placing an upper limit on the flow over all arcs representing this facility.

Mathematically, the above network problem can be described by a system of M linear equations in N variables. The arcs are represented by the variables while the nodes and capacity restrictions are described by the linear equations.

Consider a logistics network G with a set of nodes $N = \{1, 2, \ldots, n\}$ and a set of directed arcs $A = \{(i,j), \epsilon\ N \times N\}$ where i represents an origin node and j a destination node. Every arc (i,j) contained in the network has four distinct attributes.

The first is the attribute of *time* interval where T gives the number of time intervals in the study period and t is the time interval index such that $t = 1,2, \ldots, T$. These intervals could be days, weeks, months, etc.

The second attribute represents *commodity* type where K is the total number of commodities and k is the commodity index such that $k = 1,2, \ldots, K$.

The third is the attribute of geographical *location*. Here F represents the number of points defined for the study area while f is again the index of location, $f = 1,2, \ldots, F$.

The fourth attribute is chosen from a number of possibilities. It may be one of transport *mode* (m = 1,2, . . . ,M), *transshipment* (h), *warehousing* activity (w), *supply* function (s) or *requirement* function (r).

$^{x}(i,j)$ represents the quantity of flow that is actually assigned to the arc (i,j) in a solution to a given logistics problem. The set of arcs A is partitioned into a number of disjoint subsets A'_v where v = 1,2, . . . ,V. Each set represents a group of arcs with a unique type of activity or function as described below.

A'_1 is a set of *source* arcs (i,j) with associated acquisition costs $c_{(i,j)}$ and upper limits on their supply $X_{(i,j)}$ equal to $b_{(i,j)}$ where node $_i$ is always equal to I, a super source node used to conserve network flow (see Figure 1). Each of these supply arcs has the three basic attributes of time interval (t), commodity type (k) and geographical location (f) as well as a fourth denoting the supply functions (s). For example, the supply $X_{(i,j)}$ of commodity k = brand X during time interval t = 2 at point f = city y might be limited to $b_{(i,j)} = 100$ tons at a cost $c_{(i,j)} = \$20$ per ton.

The supply bounds are written:

$$0 \leqslant X_{(i,j)} \leqslant b_{(i,j)},\ (i,j)\ \epsilon A'_1 \qquad (1)$$

A'_2 is a set of *destination* arcs (i,j) with requirements $X_{(i,j)}$ equal to $b_{(i,j)}$ where node j is always equal to J, a super sink node used to conserve network flow. (See Figure 1). The cost $c_{(i,j)}$ associated with destination arcs is usually set to zero. Each of these arcs (i,j) also has the attributes of time interval t, commodity k and location f as well as the functional attribute denoting demand r. As way of illustration, the demand for commodity k = brand X during time interval t = 2 at point f = city y might be $b_{(i,j)} = 25$ tons. (cost $c_{(i,j)} = 0$).

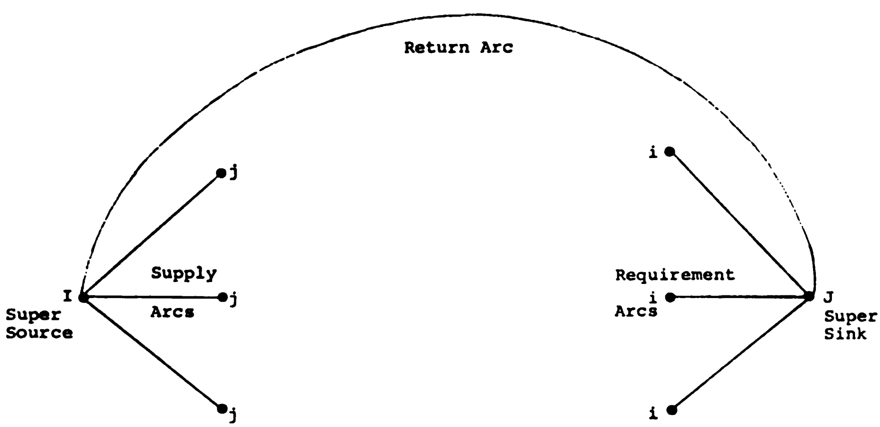

FIGURE 1: Each arc represents a supply or a demand for a particular commodity at some geographical location in a specified time interval except for the return arc (J,I) which is a dimensionless arc used to conserve network flow.

The requirement bounds are written:

$$b_{(i,j)} \leqslant X_{(i,j)} \leqslant \infty \quad , \ (i,j) \ \epsilon A'_2 \qquad (2)$$

A return arc (J,I) joins the super sink J to the super source I. This is a dimensionless arc used to conserve flow in a mathematical sense, with zero cost and no upper limit on flow (See Figure 1).

This condition is written:

$$0 \leqslant X_{(J,I)} \leqslant \infty \qquad (3)$$

Of course, if a feasible solution to a given logistics problem is to exist at all, the total demand for all commodities must be less than or equal to the total supply available during the planning period being studied.

This condition can be stated as follows:

$$\sum_{(i,j)\epsilon A'_2} b_{(i,j)} \leqslant \sum_{(i,j)\epsilon A'_1} b_{(i,j)} \qquad (4)$$

A'_3 is defined as a set of *transport* arcs (i,j) with associated costs $c_{(i,j)}$ and if applicable, an upper limit on individual arc flow $X_{(i,j)}$ equal to $b_{(i,j)}$. (See Figure 2).

Such an arc could represent the possibility of shipping a commodity k = brand X from location f = city y to f = city z during time interval t = 2 by mode m = rail at a cost of $c_{(i,j)}$ = \$8/ton. If the total rail capacity between these two cities in this particular time interval was limited it could be stated as follows:

$$0 \leqslant X_{(i,j)} \leqslant b_{(i,j)}, \ (i,j)\epsilon A'_3 \qquad (5)$$

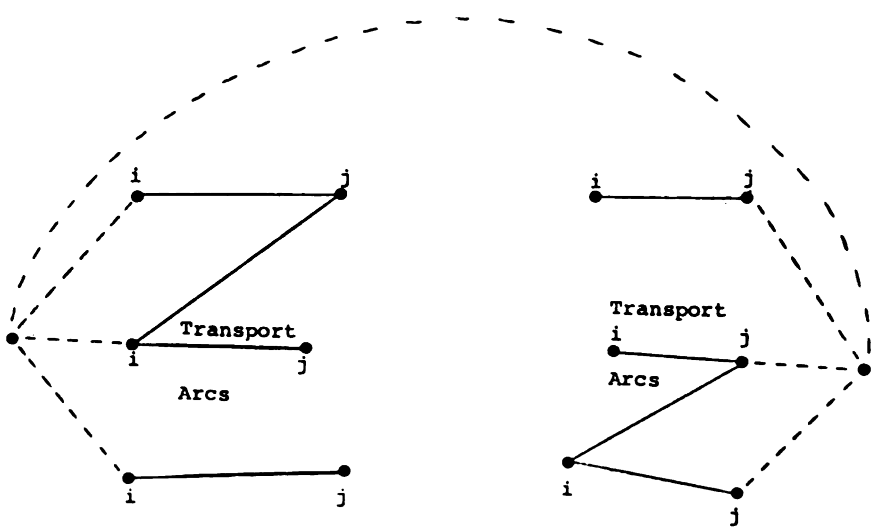

FIGURE 2: Each arc (i, j) represents a possible movement by a particular mode between two geographical locations. Commodity type and time interval are defined for each arc as well.

A'_4 is a fourth set of arcs (i,j) representing commodity *transshipments* (h). Such transfers incur a per unit cost $c_{(i,j)}$ and can have an upper bound $b_{(i,j)}$. (See Figure 3).

Such an arc might represent the transfer of a commodity k = brand X from mode m = rail to mode m = truck at geographical location f = city y in time interval t = 2 at a cost of $c_{(i,j)}$ = \$2/ton. If the facility at f had a capacity restriction on this particular commodity in this specified time interval it would be represented as:

$$0 \leqslant X_{(i,j)} \leqslant b_{(i,j)},\ (i,j) \epsilon A'_4 \qquad (6)$$

The final disjoint set A'_5 represents the *stockpiling* or *warehousing* function (w). An arc (i,j) contained in this set could represent the storage of commodity k = brand x from time interval t = 3 to time interval t = 4 at location f = city y. The associated cost might be $c_{(i,j)}$ = \$2/ton with a facility limitation for this particular commodity, location, etc., of $b_{(i,j)}$ = 40 tons. (See Figure 4).

Mathematically this condition is written:

$$0 \leqslant X_{(i,j)} \leqslant b_{(i,j)},\ (i,j) \epsilon A'_5 \qquad (7)$$

In order that commodities are not created or destroyed by the network model it is necessary to write conservation of flow equations for each node

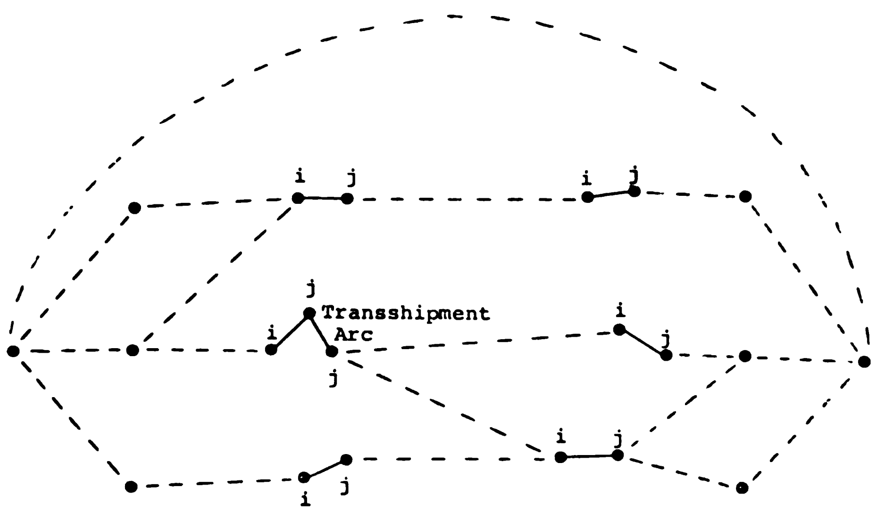

FIGURE 3: Each arc (i, j) represents transshipment between different transport modes or from a transport mode to a stockpile or warehouse. Commodity type, time interval and geographical location are also defined for each arc.

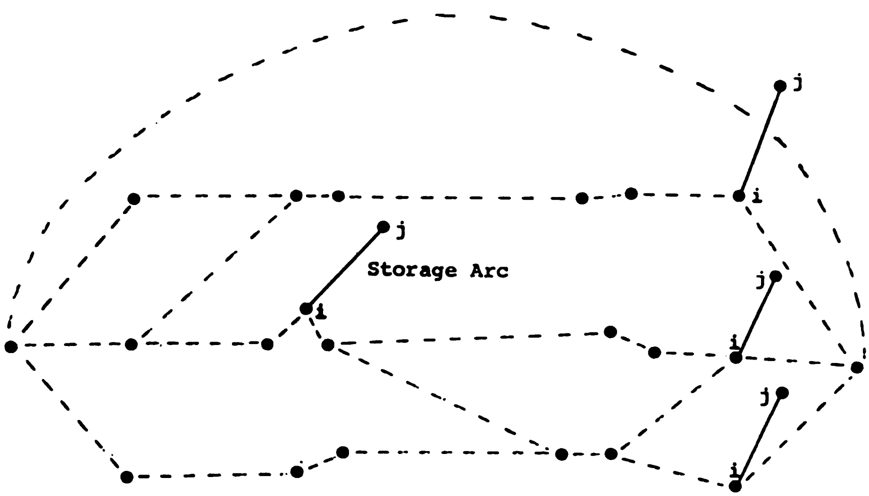

FIGURE 4: Arcs (i, j) represent the storage of a commodity from one time interval to another at a specified geographical location. The arcs representing the next time interval are not shown in the above diagram.

in the network. These equations stipulate that all movement into a node must equal all movement out of a node and are written as follows:

$$\sum_{(i,j)\epsilon Q'_j} X_{(i,j)} = \sum_{(i,j)\epsilon Q''_j} X_{(i,j)}, \; j = 1,2, \ldots ,N \qquad (8)$$

where Q'_j is the set of incoming arcs incident on node j
and Q''_j is the set of outgoing arcs incident on node j.

In order to represent transport plant and equipment restrictions, warehousing capabilities, etc., it is often necessary to place one limit on the total flow over the group of arcs representing a particular resource. Consider as an example, a truck fleet operating in a given region that is able to handle 5 commodity types with varying weight and volume characteristics. In order to limit the transport capability of the entire fleet, the flow of goods over all arcs representing all possible movements of the 5 commodities throughout a specified number of time intervals is restricted. Coefficients account for both the differences in weight and bulkiness of the commodities as well as for the varying cycle times of the individual moves.

The above types of limitations are included in the model in the following manner.

Let $A''_p \epsilon A$ represent the set of arcs in the p th group constraint and let b'_p be the mutual capacity limitation upon the arcs in the p th group, $p = 1,2, \ldots ,P$. Furthermore, let the coefficients $u_{(i,j)}$ represent the manner in which arc (i,j) uses the resource b'_p. For example, if a base arc coefficient is defined as one and a particular truck movement represented twice as many miles as the base and the produce is twice as bulky it would need 4 times the number of trucks as the base movement. Consequently the coefficient $u_{(i,j)}$ would be equal to 4 in this case.

These group constraints are written:

$$\sum_{(i,j)\in A''_p} u_{(i,j)} X_{(i,j)} \leqslant b'_p, \quad p = 1,2, \ldots ,P \qquad (9)$$

Restrictions on truck fleets, rail equipment, barges, warehouses, etc., can be represented by the above type of equation. Other types of limitations can also be included if such limits can be satisfactorily modelled by the above type of linear equations. For example, some models found in the literature have attempted to model the production process to a greater extent than is done here,[2,3] while others have concentrated on improving the representation of the inventory activity.[4,5]

Logistic problems described by equations (1) through (9) generally have many feasible solutions. In other words, it is possible to move commodities from supply to requirement points using many different routes and modes. The objective, however, is to find that particular solution which satisfies the given constraints and requires the least expenditure of funds. In order to do this, an *objective function* is defined by the summation of all variables multiplied by their associated costs, and the technique of linear programming is used to minimize this function, which is written as follows:

$$\text{Min } Z = \sum_{(i,j)\in A} c_{(i,j)} X_{(i,j)} \qquad (10)$$

APPLICATION

The discovery of oil and gas reserves at Prudhoe Bay on the North Slope of Alaska has generated a number of pipeline proposals. The Gas Arctic Systems Study Group is preparing one of the gas pipeline proposals and Canadian National, as a member of the group, is concerned with the logistics of supplying the material and equipment needed during the construction of the line.[6,7]

The proposed route would extend for approximately 1550 miles between the North Slope of Alaska and northern Alberta (See Figure 5). The line itself would involve two types of forty-eight inch diameter pipe (low and normal-temperature steel) while other supplies and equipment would add about five more commodity categories (e.g., cement, construction equipment, camp facilities). The applications discussed here include only the two types of steel pipe, although computer runs have been made with seven commodities. Construction would extend over two and one half years with the major part of the work taking place in the final two winter seasons. At present, five time intervals consisting of two summer and three winter periods are represented in the model.

The fifteen stockpiles shown in Figure 5 have a known tonnage requirement of one type of steel pipe in each of the final two winter construction periods. Furthermore, a given percentage of the pipe requirement must be in the stockpile by the beginning of a winter construction period. (i.e., 50% in these applications). Japan is the only source for the low temperature pipe

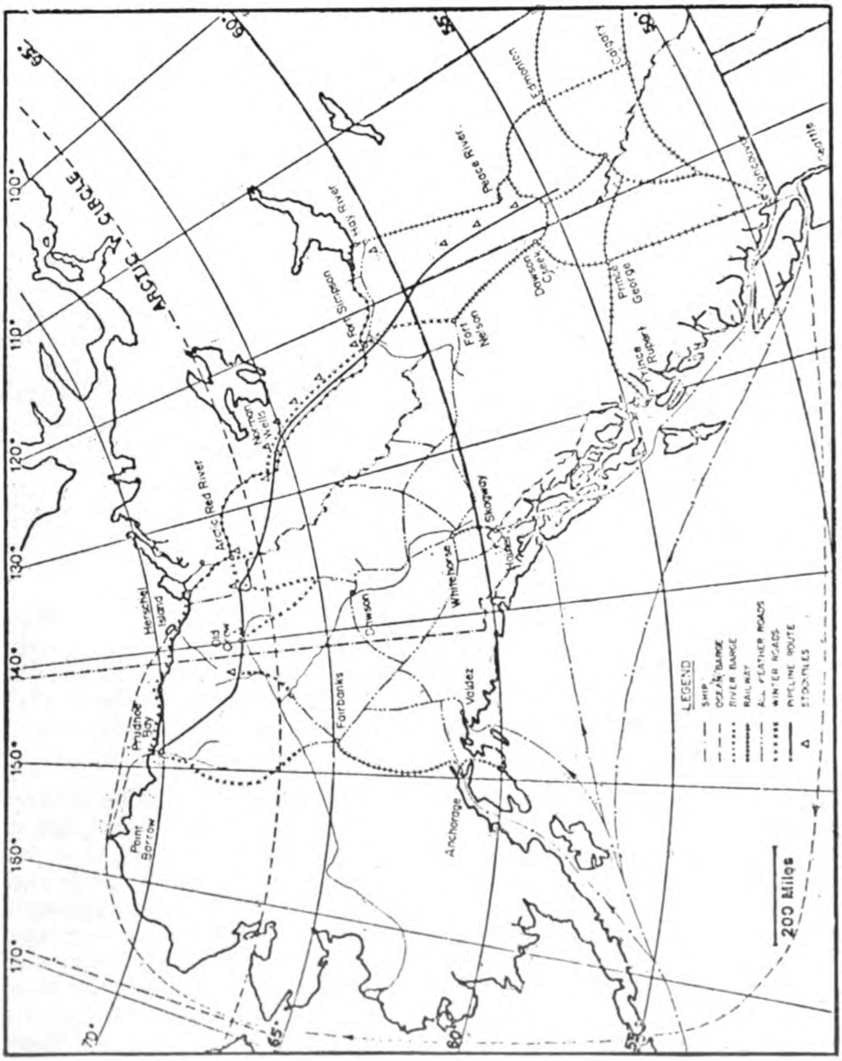
ARCTIC CIRCLE
Point Barrow
Prudhoe Bay
Herschel Island
Old Crow
Fairbanks
Dawson
Whitehorse
Skagway
Haines
Valdez
Anchorage
Arctic Red River
Norman Wells
Fort Simpson
Hay River
Peace River
Edmonton
Calgary
Dawson Creek
Fort Nelson
Prince George
Prince Rupert
Vancouver
Seattle
200 Miles
LEGEND
SHIP
OCEAN BARGE
RIVER BARGE
RAILWAY
WINTER ROADS
PIPELINE ROUTE
STOCKPILES

FIGURE 5

with unlimited supplies, while there are five Canadian sources for the normal temperature pipe, each with limited supply capabilities.

The transport network involving six modes is shown in Figure 5 as well. This network has many transshipment points and a number of warehousing locations, some with capacity limitations. Capacity restrictions are also imposed on the Mackenzie River barge system, on all railroads involved and on the three truck "pools" defined for the Mackenzie, Yukon and Alaskan geographical areas.

As mentioned earlier, one objective of a project co-ordinator is to determine a minimum cost set of commodity routings which do not violate any of the specified problem restrictions. Figures 6(a), (b), & (c) represent in graphical form, commodity routings produced by the "Base Run" for the pipeline logistics problem described above. Only a few of the routings generated by the model for movements occurring in the initial two time intervals are included in the diagrams. Construction of the line does not occur until the 3rd time interval (i.e., 2nd winter season) but two start-up periods are necessary, because of the existence of some winter trails, transport equipment restrictions, and the stipulation that 50% of material requirements be in a requirement stockpile by the beginning of a construction period.

Figure 6(b) shows 35,200 tons of low temperature steel arriving in Vancouver from Japan. The pipe is transferred to CN and transported to a staging

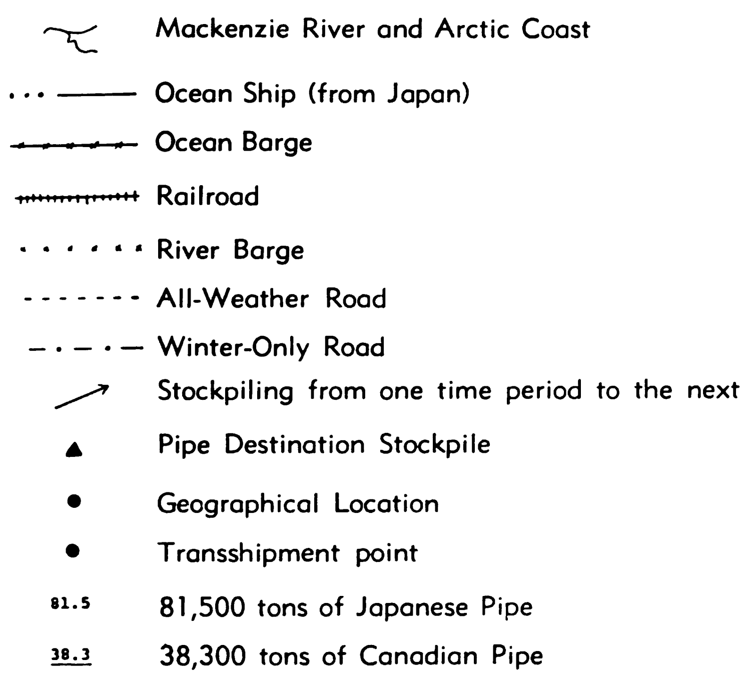

FIGURE 6(a): Legend for Figures 6(b) & (c)

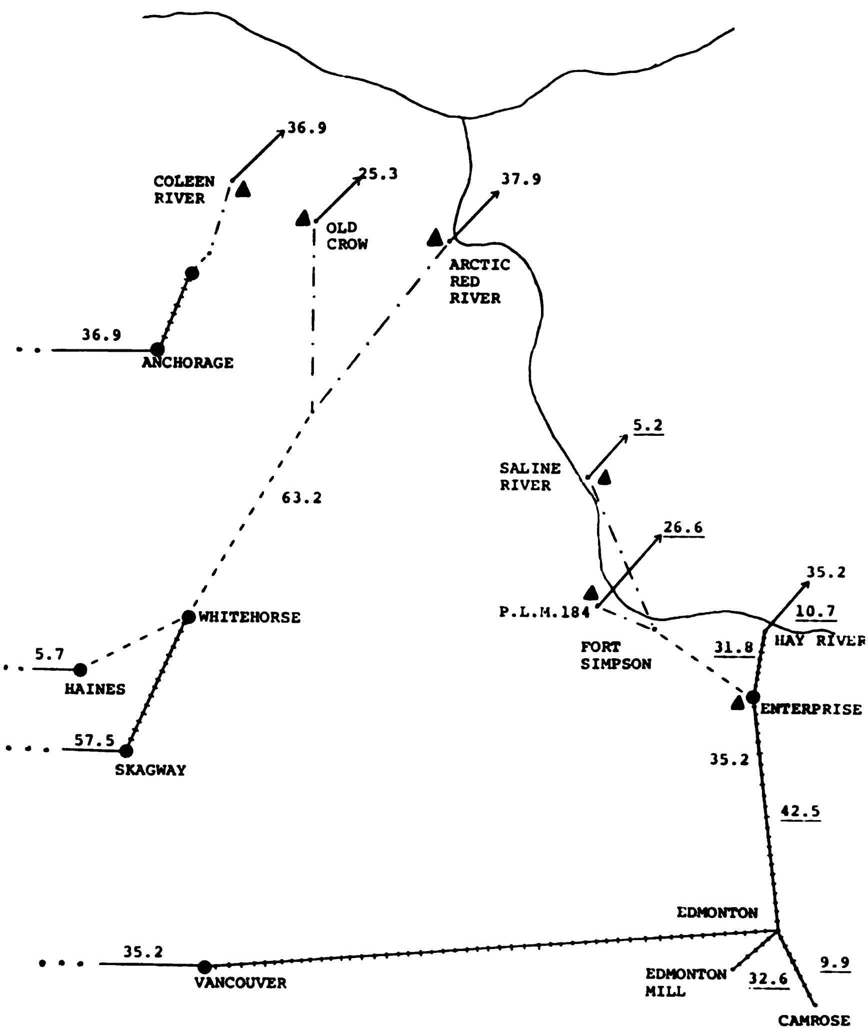

FIGURE 6(b): Selected pipe movements from "Base Run," 1st time interval (winter)

area at Hay River where it is held over to the next time period (i.e., summer) for shipment by Mackenzie River barges (see Figure 6(c)).

This pipe is brought into Hay River one full period before it can be shipped on the river because of the restriction placed on rail car resources in this computer run. Consequently, the summer rail movement backs up into the winter period. It can also be seen from Figure 6(b) that a quantity of pipe moves to Enterprise, is transferred to truck and transported to both the Pipe Line Mile 180 and Saline River stockpiles during the first winter period although the pipe is not needed until the second period. There are three

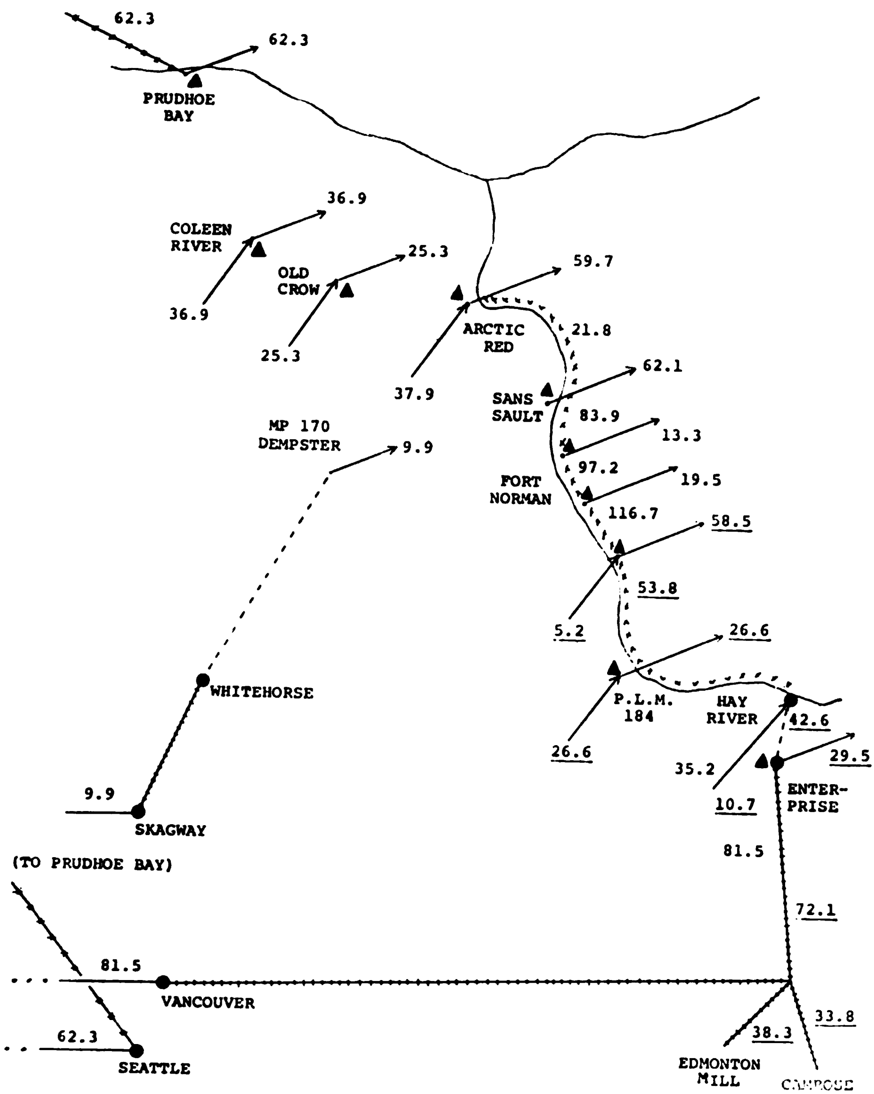

FIGURE 6(c): Selected pipe movements from "Base Run," 2nd time interval (summer)

main reasons for these early shipments. In the first place the Mackenzie barge system cannot handle all of the traffic that might go by river. Secondly, there is the stipulation that 50% of the required pipe be in stockpile by the beginning of a construction period. And thirdly, the fact that these two locations can only be reached over land by winter roads forces a quantity of pipe to move in one year before it is actually used. The model uses the more expensive truck routes for the shorter hauls in the upper Mackenzie River area while it assigns pipe to the barges for the longer moves (See Figure 6(c)).

A significant quantity of pipe moves into the west coast ports of Skagway, Haines and Anchorage in the first winter period and is transported by a number of modes to requirement stockpiles. It is then held over until the third time period when it is finally used. The volume represents the 50% inventory limit and the movements take place early because of the existence of winter-only roads in the vicinity of the pipeline route. Many more comments could be made regarding particular routings shown in Figure 6 as well as for those not represented in the diagrams, but hopefully these examples indicate the kinds of insights a project co-ordinator might obtain about various commodity routings. In order to compare the Base Run to subsequent runs, a breakdown of costs by mode and activity is shown for each run in Figure 7.

The model can identify and quantify transportation and auxiliary facility needs. Figure 8 gives an example of the transport resources implicit in the solution generated by the Base Run. Other reports not included here can break this summary down to show equipment requirements and associated costs for particular regions or moves. This information is especially useful if equipment needs are large and lead times (i.e., the time necessary to establish or produce some of the items) are significantly long, as is the case for Mackenzie River barges and tugs.

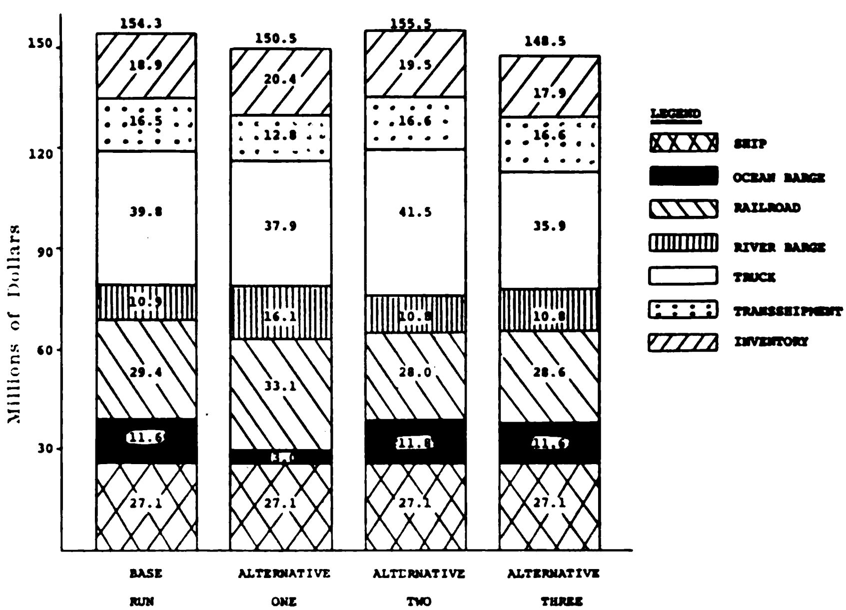

FIGURE 7: Summary costs for four computer runs.

SUMMARY OF EQUIPMENT UNITS REQUIRED—(BASE RUN)

	TIME PERIOD					
	W 73/74	S 74	W 74/75	S 75	W 75/76	Maxi-mum
Ocean Ship	2.3	2.8	3.6	2.2	1.8	999.0
Ocean Barge		6.2		3.9		999.0
Rail Cn. Jpn.	60.2	139.6	110.3	139.6		140.0
Rail Cn. Cdn.	18.3	30.0	30.0	30.0	30.0	30.0
Rail Cn. Edm.	79.8	108.3	108.3	106.6	105.3	120.0
Rail Pge.						35.0
Rail Wpy.	27.9	4.8	27.9		24.6	28.0
Rail Ar.	16.9		24.7		24.7	25.0
River Barge		24.0		24.0		24.0
Truck N.W.T.	11.3	4.0	40.1	5.6	18.3	40.0
Truck Yukon	50.0	3.2	50.0		35.0	50.0
Truck Alaska	42.0		100.0		100.0	100.0

FIGURE 8

The information contained in the summary of required equipment units can lead to other useful types of analyses. It shows for example, that the available number of river barges (24) is completely utilized during the two summer periods. Consequently one might be interested in measuring the benefit or reduction in transportation cost that would accrue from investing in more river barges. A computer run was made with this objective in mind where the number of barges was increased from 24 to 36. The total transportation cost decreased from $154.3 million to $150.5 million, a reduction of almost $4M. Of course, the cost of the extra barges would have to be weighed against this saving.

Such an investment changes many of the commodity routings and all impacts would have to be studied before the true benefit could be defined but the logistics model does allow one to investigate these changes in a systematic manner. One of the "secondary" effects produced by increasing the river barge fleet is the almost total reduction in pipe movement by ocean barge from Seattle around Point Barrow to Prudhoe Bay, a move which is relatively expensive and dependent on Arctic ice flow conditions.

The Base Run includes a competitive P.G.E. rail cost for pipe movement between Vancouver and Fort Nelson in northern British Columbia, but since this rate combined with the trucking costs to Mackenzie River requirement points is fairly expensive, no pipe is moved via this route. In order to demonstrate the model's ability to measure, quickly and effectively, the impact of a carrier's rate bid, the P.G.E. rail rate between Vancouver and Fort Nelson was decreased by $10/ton (i.e., by 30%) with the stipulation that at least 50,000 tons of pipe would be carried at this low rate. Alternative Two shown in Figure 7 indicates that instead of reducing transportation costs, they are actually increased by slightly over one million dollars. The largest increase is in trucking costs, although other modes and activities change as well and could be thoroughly studied by referring to the various reports produced by the logistics model. This type of comprehensive analysis would be useful both before and during project implementation as new conditions and situations were encountered.

Much of the northern part of the proposed pipeline can only be reached by winter roads, a condition which greatly restricts movement in the area not only for the pipeline project but for everyone living and operating in the region. Since the Canadian government is building all-weather roads in the north it might prove useful to calculate the savings that could accrue to this project if selected road links were completed before project implementation. As an example, Alternative Three in Figure 7 shows that almost $6M could be saved if the Dempster Highway between Dawson City in the Yukon and Arctic Red River in the North West Territories was completed as an all-weather road. Most of the saving results from reduced trucking costs and inventory levels although many other "secondary" impacts are indicated by the various model reports.

The model could be used as well, to measure some of the effects of acquiring more steel pipe from Canadian mills, if such a policy was deemed in the national interest. The "added" cost to the pipeline project could be weighed against increased benefits going to Canadian carriers, pipe suppliers and the economy in general. Although other examples of the model's ability to do sensitivity analysis could be given, the above illustrations should point out the kinds of information that can be obtained from the model. In practice, individual logistics problems will usually suggest additional types of analyses useful to the particular problem being studied.

CONCLUSION

A logistic problem has been formulated as a linear programming model capable of analyzing many of the questions associated with large-scale distribution problems. The model formulation is open-ended, in that it can include conditions peculiar to a specific study if it is felt such aspects can be satisfactorily represented by linear relationships. The model has been used with considerable success as an aid in logistics planning for an Arctic pipeline. Computationally, the model proved very efficient in this application, requiring less than one minute of CPU time on an IBM 370-165 computer to solve the two-commodity problem, and less than 5 minutes for the seven-commodity problem. It would appear that this type of model could be useful in a large number of studies involving logistics planning.

REFERENCES

1. A number of actual logistic problems are discussed by Alan H. Gysfert, "Business Logistics for Better Profit Performance", *Harvard Business Review*, vol. 46, 75-84. Nov.-Dec. 1968.
2. Charles H. White, "Production Allocation with Set-Up Penalties and Concave Material Costs", *Operations Research*, vol. 17, 958-972, 1969.
3. Carl F. Meyer, "A Model for Production-Distribution Networks with Transit Billing", *Management Science*, vol. 14, B204-B218, 1967.
4. R. Fetter, "A Linear Programming Model for Long Range Capacity Planning", *Management Science*, vol. 7, 372-378, 1961.
5. A. Veinott Jr. and H. Wagner, "Computing Optimal (s,S) Inventory Policies", *Management Science*, vol. 11, 525-552, 1965.
6. R. J. O'Rourke who is located in CN's Edmonton offices is logistics Project Co-ordinator. For a more detailed description of the transportation problems involved in building the proposed line see, R. J. O'Rourke, Logistics Planning For a Northern Pipeline", *The Journal of Canadian Petroleum Technology*, July-Sept., 1971.
7. A few of the technical problems of pipeline building in northern regions are discussed in W. John Keys, "Problems of Pipe Lining in Northern Canada", *Transportation Research Forum/Papers*, vol. 10, 319-326, 1969.