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IDEALIZED AIR COMMUTER NETWORK FLOWS IN A REMOTE SPATIAL SETTING

Dale R. Schmeichel and R. Keith Semple*

Abstract

Remote mining projects use air commuting to transport the workforce to and from mine sites in the uranium mining industry in the province of Saskatchewan. This paper uses a capacitated network flow algorithm to examine passenger flow patterns in the commuter networks and to develop least cost proposed network configurations which would result in considerable savings on annual air transportation costs compared to present routing patterns.

Introduction

The purpose of this paper is to develop an integrated least-cost air commuter network for transporting mine workers to three of the largest operating open-pit uranium mines in the world located in northern Saskatchewan. At present, chartered air carriers operate a separate commuter network for each mine. The research demonstrates that these networks operate in a feasible, but less than optimal, least-cost fashion and that an integrated system would reduce costs even further. A graph theoretic model forms the basis of the separate and integrated air commuting networks. A sensitivity analysis, based on northern Saskatchewan conditions and employing the Out-of-Kilter (OKA) algorithm, determines the optimal capacitated least-cost flows in the proposed systems.

Background

In Saskatchewan, workers began commuting by air to uranium mines in 1975. Figure 1 shows the air routes not in use and the location of each mine in relation to small northern communities and to the larger more southernly centers of Prince Albert and Saskatoon. In the Northwest Territories (NWT), six of the 10 operating mines also use some type of air commuting. Virtually all frontier oil exploration and off-shore drilling projects in the NWT utilize air transportation systems (7).

* Geography Department, University of Saskatchewan

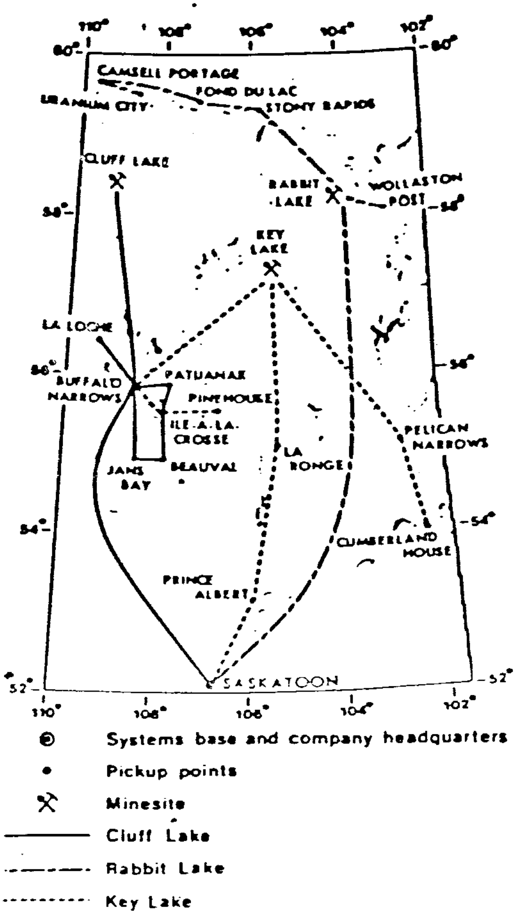

Figure 1: Air Commuter Systems in Northern Saskatchewan.

Air commuting is the use of aircraft to transport workers from their place of residence to a worksite and back again on some regular basis. It is sometimes used interchangeably with the term rotation work schedule but may more appropriately be thought of as the transportation system used to enable the shift changes required to implement a rotation work schedule. Mines in Saskatchewan employ two rotational shifts, each consisting of a seven day work period, eleven hours per day, followed by seven days off back in the community of residence. Accommodation and recreational facilities are provided at the mine site.

Air commuter systems offer advantages over construction of new permanent townsites in association with remote mining ventures. Mining companies benefit from reduced construction and operating costs as a result of such systems. Jim Goebel, Personnel Manager for the Key Lake Mining Corporation, reports turn-over rates are less than thirty percent annually using air commuting. This compares to turn-over rates greater than one hundred percent for many isolated mining projects where permanent towns have been constructed to house workers and their families [4]. Government social overhead expenditure is also reduced since new public facilities are not needed. Mining families enjoy the advantages of living in stable, urban centers with a wide range of amenities. This system permits a "normal" life for families who traditionally have had to live with the harsh realities of a northern mining town existence. Indigenous people benefit from provincial governmental policy which provides for northern native hiring quotas in development agreements for the mines. Because of these agreements, mining companies have established worker pickup points in several northern communities rather than just in Prince Albert and Saskatoon.

Long term economic prospects for the uranium industry in Saskatchewan are very good. Gordon Leiast, Sales Manager for the Saskatchewan Mining Development Corporation, indicates the province has about fifteen percent of the current annual productive capacity of the non-communist world. Deposits are near the surface with grades far above world averages permitting low cost open-pit mining. As a result, the local industry is prospering even at a time of globally depressed uranium prices. Related businesses, such as air carriers, expect continued growth in demand for their services from this industry.

Table 1 lists the number of uranium mine employees by pickup point and by the A or B shift for each mine. Three mining companies, Amok Ltd.,

TABLE 1
Uranium Mine Employees by Pickup Point at December 1985

Pickup Point	Cluff Lake (Amok)		Key Lake (KLMC)		Rabbit Lake (Eldor)		Total	
	A	B	A	B	A	B	A	B
Saskatoon	98	100	149	138	107	99	354	337
Buffalo Narrows	9	16	6	10	—	—	15	26
Beauval	23	13	—	—	—	—	23	13
Ile a La Crosse	11	6	5	6	—	—	16	12
Jans Bay	4	7	—	—	—	—	4	7
La Loche	3	4	—	—	—	—	3	4
Patuanak	6	3	—	—	—	—	6	3
Prince Albert	—	—	46	56	27	34	73	90
La Ronge	—	—	17	13	—	—	17	13
Cumberland House	—	—	3	6	—	—	3	6
Pelican Narrows	—	—	2	6	—	—	2	6
Pinehouse	—	—	5	1	—	—	5	1
Wollaston Post	—	—	—	—	4	8	4	8
Uranium City	—	—	—	—	2	1	2	1
Camsell Portage	—	—	—	—	2	1	2	1
Fond du Lac	—	—	—	—	7	10	7	10
Stony Rapids	—	—	—	—	20	20	20	20
Totals	154	100	233	236	169	173		

Source: Personnel Records, Saskatchewan uranium-mine operating companies.

Key Lake Mining Corporation and Eldor Ltd., charter air carriers based in Saskatchewan communities to transport workers from their home town to the mine site and back for both shifts. Saskatoon provides a southern base for this system. Table 2 contains a listing of relevant Saskatchewan carriers and gives the tariff charges for each available aircraft.

TABLE 2

Saskatchewan Air Carriers Tarriff Schedules by Licensed Base, Aircraft Type and Seating Capacity at December 1985

Carrier	Base	Aircraft Type	Seating Capacity	Tariff per mile
High Line Air	Saskatoon	Cv-640	54	$7.00
		Cv-600	44	6.45
		F-27	40	6.10
		Bandit	18	2.75
		Queen Air	8	2.12
Athabaska Airways	Saskatoon	Cessna 404	10	2.48
	Prince Albert	Cessna 310	5	1.80
	Buffalo Narrows	King Air	6	2.46
	La Ronge	Single Otter	10	3.13
		Twin Otter	18	3.57
Buffalo Narrows Airways	Buffalo Narrows	Single Otter	10	3.06
		Baron	5	1.70
		Chieftain	9	2.40
C&M Airways	La Loche	Cessna 206	6	1.25
		Navajo	7	1.80
		Single Otter	10	2.75
Prairie Flying	Nipawin	Cessna 310	5	1.73
		Queen Air	7	1.75
Jackson Airways	Sandy Bay	Beaver	6	2.18
		Cessna 310	5	1.86
		Single Otter	10	3.00
Nipawin Air Services	Uranium City	Single Otter	10	2.75
	Stony Rapids	Twin Otter	18	3.57
Eagle Air	Wollaston Post	Single Otter	10	2.75
		Cessna 210	6	1.45
Pinehouse Air	Pinehouse	Chieftain	9	2.40

Source: Saskatchewan-based charter air carriers.

The Canadian Air Transport Commission (CTC) requires all air carriers to file, justify and comply with tariff schedules which contain per mile rates and other charges for each type of aircraft. Partial deregulation permits some discounting from published rates which results in mining companies paying somewhat less than the announced tariffs. The CTC also grants licenses to charter carriers to operate out of one or more bases where business volume is sufficient [1]. If a flight begins from a community which is not a licensed base for the carrier used, the customer is charged a fee, known as a positioning charge, in addition to the regular charter cost. If the town in which the flight is initiated has no licensed carrier, the positioning charge need not be levied. Usually, however, the carrier does charge for such flights. This policy has implications for the uranium industry since several of the pickup points in northern Saskatchewan are too small to support a licensed carrier.

Modeling the Air Commuter Networks

Graph theory provides a means of modeling the nodes and arcs of the air commuter networks [3]. The origin communities and the destination mine sites are the nodes. The air links are the arcs. Each origin has a worker population which is the number of employees resident at that pickup point. Each destination has specific demands for miners on each rotational shift, and each arc has a commuter capacity determined by the maximum size of plane the airstrip can accommodate. The Out-of-Kilter Algorithm provides the basis for determining the least-cost capacitated solution to the air commuting problem in graph theoretic form. The OKA permits upper and lower arc capacity constraints required for this analysis and it is ideal for performing network sensitivity analysis necessary to alter the networks iteratively to obtain acceptable solutions.

Howard Gauthier [2] introduced the use of the OKA to geography with his analysis of maximum flow capability of the Brazilian road network connecting São Paulo and two interior regional centres. As part of his analysis of intraurban accessibility, William A. Muraco [6] employs the OKA to determine minimum travel time between selected nodes in the highway networks of two American cities. King *et al.* [5] expanded the theoretical use of the OKA to take into consideration storage costs. They determined the least-cost flow pattern for coal movement and storage at intermediate nodes in a multi-modal transportation network within the Great Lakes region. The analysis treats storage costs as flows through time and links these temporal flows to the normal spatial flows through a bi-modal transport system. Sinclair and Kissling [8] use this method to determine an optimal fruit storage and distribution system for New Zealand, where storage costs are very important. The spatial-temporal model optimizes distribution patterns and storage locations simultaneously. Like the coal-haul study, multi-modal transportation methods are involved in the network analysis.

The air commuter study follows the tradition of Gauthier and Muraco in using the OKA to determine optimal spatial flow patterns in a single transportation mode environment. It has in common with Sinclair and Kissling and King *et al.* an interest in determining the optimal flow through a network. Unlike these earlier studies, network configuration is not fixed. Charter aircraft routes can quickly and easily change. Furthermore, analysis must take into account unique circumstances such as the northern hiring constraints and aircraft positioning charges. Figure 2 demonstrates the use of the OKA for a sample problem exhibiting characteristics found in a typical air commuter system with shift changes. The mathematical specification for the sample problem may be expressed as:

Objective:	$\text{Min } Z = \Sigma_{ij} c_{ij} x_{ij}$	∇_{ij}	(1)
Subject to:	$l_{ij} < x_{ij} < u_{ij}$	∇_{ij}	(2)
	$\Sigma_{ij} x_{ij} - \Sigma_{ij} x_{ji} = 0$	∇_{ij}	(3)

Z = total cost of network flow

c_{ij} = cost per unit of flow on arc (ij)

l_{ij} = minimum capacity on arc (ij)

u_{ij} = maximum capacity are (ij) can accommodate

x_{ij} = flow on arc (ij).

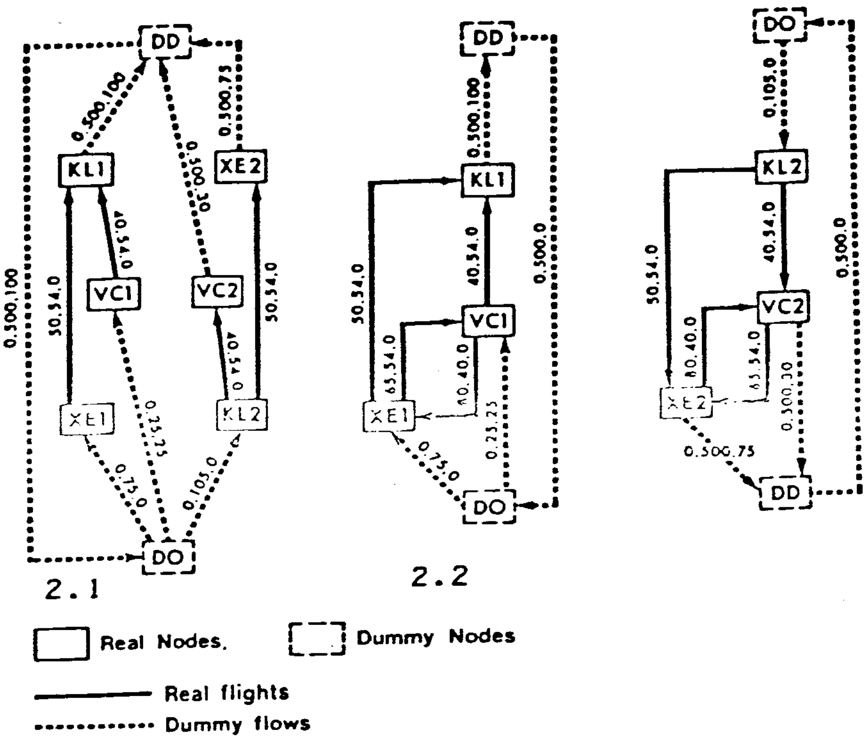

Figure 2: The Capacitated Transportation Problem.

Figure 2.1 depicts the air network modeled as the Round Trip Capacitated Transportation Problem (RCTP). One destination node, KL1, represents a mine site KL at time period 1. Two origin nodes XE1 and VC1 represent the seventeen real world pickup points at time period 1. Upper capacity arc constraints on arcs from the dummy origin (DO) to each real origin model the availability of workers. The lower capacity constraint on the arc KL1-DD specifies the demand requirement for the given shift. Since these demand and supply arcs do not represent real flows in the physical system being modeled, the cost parameter on such arcs is zero. Let VC1 represent pickup points within northern Saskatchewan. A positive lower capacity on the supply arc for VC1 models the northern hiring constraint. There is no requirement to hire workers from XE1 and therefore the lower capacity on this supply arc is zero. Those arcs which represent real flows in the physical system have arc parameters reflecting real physical constraints. Each arc has an upper capacity equal to the lessor of available aircraft seating capacity or the size of the aircraft which can land at the airstrip in the destination community. The cost parameter is the per passenger cost associated with the particular aircraft used on the route in question. The lower capacity constraint is usually zero which indicates that a specific route need not be utilized in any given situation.

Once the planes arrive at the site, they represent the only available aircraft to return the cross-shift employees to their respective pickup points for the seven-day rest period. Thus, KL2 now represents the mine site as the origin of all cross-shift employees, and XE2 and VC2 become destinations. The specification of parameters on arcs connecting the subscript "2" nodes follows from the descriptions given above. Since the OKA operates on a circulation principle, DD-DO is required to meet the conservation of flow constraint. It must have an upper capacity at least equal to the sum of all demand. Again, since it does not represent a real flow, the cost parameter is equal to zero. Figure 2.2 demonstrates that the RCTP is actually two separate One Way Capacitated Transportation Problem (OCTP) formulations. Using the OCTP, it becomes possible to route the return trip of each aircraft independently of the route followed in arriving at the mine site. This study utilizes the OCTP formulation in the examination of passenger flows in the real physical systems.

Case Study of the Saskatchewan Air Commuter Networks

Analysis of Present Routing

Table 1 provides the raw data for modeling the networks presently in use. A and B shift employees are not all changed in one day. This shifting pattern reflects two considerations. First, the largest aircraft currently available from Saskatchewan carriers is the 54-seat Convair 640s of High Line Air. The second consideration reflects the desire to maintain frequent transportation links between administration offices in Saskatoon and the mine sites. Figure 3 depicts the network of the Key Lake Mining Corporation. Presently, flights depart from Saskatoon each weekday, making stops in Prince Albert and La Ronge on Tuesdays and Thursdays and only in Prince Albert on the other days. The northern routes, making three trips weekly, operate independently of the main line.

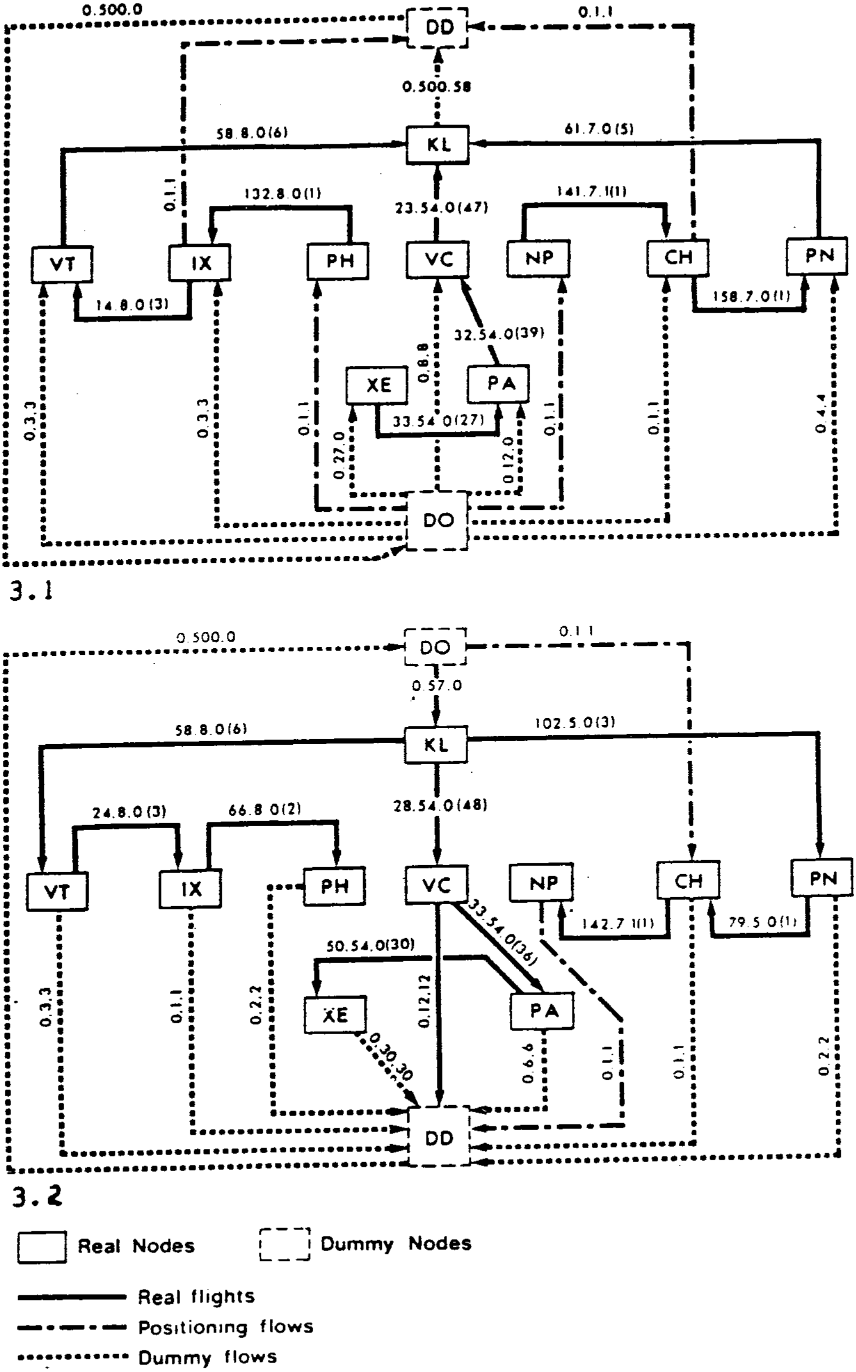

Figure 3: The Tuesday Network for the Key Lake Mine.

Figure 3.1 shows the OCTP model of the present routing for the Tuesday incoming B-shift flights. Figure 3.2 shows the Tuesday A shift returning flights. The volume of flow is shown in parentheses. Model positioning changes as follows. The licensed base receives dummy supply which "drains" off through a dummy demand arc after the positioning flight occurs. In Figure 3.1 a positioning flight occurs between Nipawin (NP) and Cumberland House (CH). Thus NP has dummy supply of one worker shown by the arc DO-NP. That dummy supply is removed from the system once the aircraft is in "position" at Cumberland House. The arc CH-DD is required for this purpose. The same technique models the flight from Pinehouse (PH) to Ile a La Crosse (IX). Real total demand is unaffected by this technique, and the results show the correct mine site demand totals and the correct total costs. The same criteria determine the upper and lower arc capacities as used in the sample network. This study calculates c_{ij} as follows:

$$c_{ij} = [(d_{ij})(r) + t + f] / x_{ij} \qquad (4)$$

where:

d_{ij} = number of miles between i and j

r = tariff (study used published rates only)

t = transport tax (8% on aircraft over 18000 lbs. gvw)

f = landing fee (excluding one free landing per flight)

x_{ij} = flow of passengers on arc (ij)

Altering an arc parameter or adding arcs permits a sensitivity analysis to search for alternate, more acceptable least-cost solutions. The only cost saving alteration discovered for this particular routing pattern is to route the eastern network through La Ronge to join the main line flight. The savings are minimal and probably not worth the loss of flexibility which may be needed should bad weather delay or cancel flights by the smaller aircraft. Larger planes using instrument flight techniques are not constrained in this fashion.

Re-aligning Weekly Flow Patterns

Significant cost savings do occur on the Key Lake network if the weekly shift-change pattern is altered. Constructing arcs from each origin node to all other nodes develops the theoretically possible network for the Key Lake mine. This network contains 64 arcs on which real flows may occur in addition to the arcs required to operationalize the model. Upper capacities are set sufficiently high on arcs from large source communities such as Saskatoon, so as not to restrict flows. If a modeled flow on such an arc exceeds the seating capacity of the largest available plane, a second plane can be added to that route in the sensitivity analysis. Adding a second plane to a particular route provides the opportunity to schedule this trip on a subsequent day. In this way the company maintains frequent contact with the mine site even with an altered shift-change schedule. Since the c_{ij} parameter is really dependent on the actual flow on any arc, the theoretical network requires the use of some c'_{ij}, an assumed value. The study obtains c'_{ij} as follows:

$$c'_{ij} = [(d_{ij})(r) + t + f] / \text{Max } x_{ij} \qquad (5)$$

Where Max x_{ij} is the seating capacity of the aircraft utilized on the arc in question. Upper capacity is also the seating capacity determined by the airstrip conditions at the destination node or the availability of aircraft at the origin node.

The initial solution of the model determines the flow patterns and cost of the optimal path through the theoretical network. Figure A shows the proposed routing for the incoming B-shift and the returning A-shift developed by applying sensitivity analysis to the solution flows on the theoretical network. When these modeled costs are compared to the sum of all present weekly modeled flight costs they produce savings of about $8000.00 per week. This represents potential savings of over $400,000.00 on total current annual air transport expenditures of just under two million dollars for this mine.

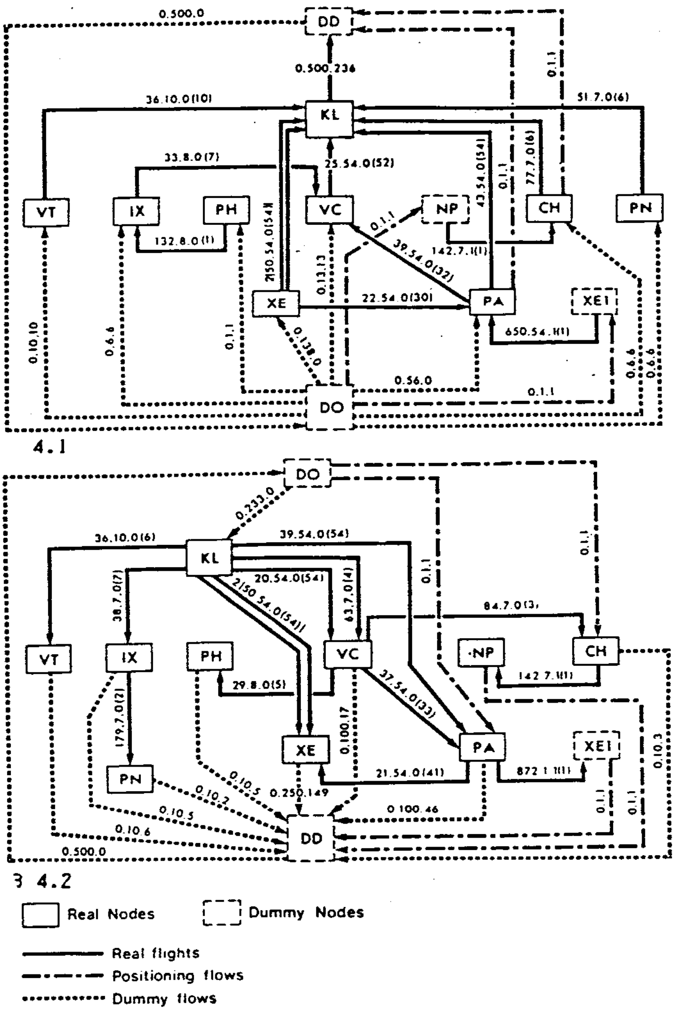

Figure 4: The Proposed Network for the Key Lake Mine.

The Integrated Network

It is theoretically possible to combine the individual routes into an integrated network by constructing arcs joining every origin to every other origin and to every destination node in the system. Similarly, the integrated network requires destination nodes be joined to each other but not to the origin nodes. Any flights leaving the mines would in fact be carrying cross-shift employees back to pickup points for their rest period. The integrated network so constructed has three real destinations for the incoming shift OCTP model. This network has 329 arcs over which real flows may occur. The study develops a proposed routing pattern for an integrated network through sensitivity analysis. Table 3 gives the proposed pattern for the incoming A shift. Arcs modeling demand and supply are not listed. The cost of this proposed network is $34,650.34. The modeled cost of the returning B-shift (not shown) is $35,077.60.

TABLE 3
Proposed Integrated Incoming A Shift Flows

Arcs	Cost	Upper	Lower	Flow
Saskatoon-Key Lake	$ 49.56	54	0	54
Saskatoon-Key Lake (2)*	49.56	54	0	54
Saskatoon-Prince Albert	38.24	54	17	17
Saskatoon-Prince Albert (2)*§	650.16	54	1	1
Prince Albert-La Ronge	34.25	54	0	36
La Ronge-Rabbit Lake	35.67	54	0	54
Cumberland-La Ronge	84.00	7	0	3
Pelican-Rabbit Lake	179.37	7	0	2
Pinehouse-Key Lake	44.29	10	7	7
Nipawin-Cumberland§	141.75	7	1	1
Uranium City-Camsell Portage	35.00	10	0	2
Camsell Portage-Cluff Lake	50.63	10	0	4
La Ronge-Pinehouse	75.00	10	2	2
Saskatoon-Cluff Lake	62.02	54	0	54
Saskatoon-Cluff Lake (2)*	62.02	54	0	54
Saskatoon-Cluff Lake (3)*	91.20	40	0	32
Saskatoon-Rabbit Lake	60.76	54	0	54
Saskatoon-Rabbit Lake (2)*	81.69	40	0	35
Saskatoon-Buffalo Narrows§	1998.28	54	1	1
Buffalo Narrows-Key Lake	24.37	54	0	54
Buffalo Narrows-Key Lake (2)*	36.25	10	0	9
Beauval-Buffalo Narrows	14.25	10	0	10
Beauval-Buffalo Narrows (2)*	14.25	10	0	10
Beauval-Buffalo Narrows (3)*	20.35	10	0	7
Jans Bay-Beauval	12.50	10	0	4
Ile a La Crosse-Buffalo Narrows	6.69	18	0	16
La Loche-Cluff Lake	10.91	10	0	3
Patuanak-Buffalo Narrows	12.50	10	0	6
Wollaston Post-Rabbit Lake	11.25	10	0	4
Fond du Lac-Cluff Lake	38.57	10	0	7
Stony Rapids-Rabbit Lake	27.25	10	0	10
OBJECTIVE = $34,650.34				

* bracketed number refers to additional flights between the same nodes.

† positioning flights — flow is removed by dummy demand arcs.

Source: Derived from OKA Sensitivity Analysis.

Adding the two totals provides the weekly cost of the proposed network. Total modeled costs of the existing independent networks for all three mines is $4,452,760 annually. This compares to an annual modeled cost of $3,642,240 for the proposed integrated system representing potential savings of 18.2 percent annually. Should the Key Lake Mining Corporation opt to implement the proposed re-aligned routing for their mine individually, the modeled cost of the existing system would be reduced by more than the $400,000 stated earlier. Subsequent implementation of the integrated network would then produce savings of about 10 percent.

Summary and Conclusions

Any implementation of an integrated network would result in some practical difficulties. Most notably, the integrated network routes all Buffalo Narrows and vicinity employees to the Key Lake mine. In actual fact, all but thirty-three A-shift employees from this area are employed at the Cluff Lake mine. Therefore any implementation of an integrated system would involve either departure from the proposed flow pattern and/or negotiations on the trading of workers from one company to another.

Another difficulty that would be encountered is loss of flexibility such as separation of the northern routes from mainline routes originating in Saskatoon. The Key Lake Mining Corporation considers retaining this separation important. Amok doesn't hold such a view since their existing network is fully integrated with the main line making one stop in Buffalo Narrows to pick up northern employees already transported there on feeder routes.

Examination of the number of flights in the real physical system also provides interesting insights. Including those arcs on which more than one flight occurs, the proposed integrated network requires 32 flows per week. The proposed Key Lake network requires a total of thirteen flights per week compared to nearly forty flights per week on their existing network. The main reduction in flights that would occur if proposed routing patterns were adopted results primarily from change to flow patterns between northern communities. Proposed networks would utilize one flight weekly between northern communities. This compares to existing routing patterns in which each company makes about three flights each week to such communities. The proposed network for Key Lake would utilize four flights per week originating in Saskatoon rather than five which is now the case. The frequency of flights from southern communities would be only marginally altered. Therefore the present network configurations may be viewed in large part ot be subsidization of northern air carriers by the mining companies.

This paper develops a procedure to analyze air commuting networks to northern uranium mining sites in Saskatchewan. A sensitivity analysis provides insights on how costs may be reduced in the current system. While costs associated with the solutions produced by the model will differ from the actual due to tariff rate discounts, this could easily be rectified in any applied situation by access to the actual rates charged. The flow patterns predicted for the re-aligned shift change at Key Lake and for the proposed integrated network represent significant potential savings compared to the modeled costs of the presently used networks. The paper provides a methodology that permits mine operators to compare their current network configurations against ideal alternates. In the present case study, the savings in total costs to the industry are significant.

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