Optimizing Feeder Movements at Front Range Aggregates' Open Pit Mine

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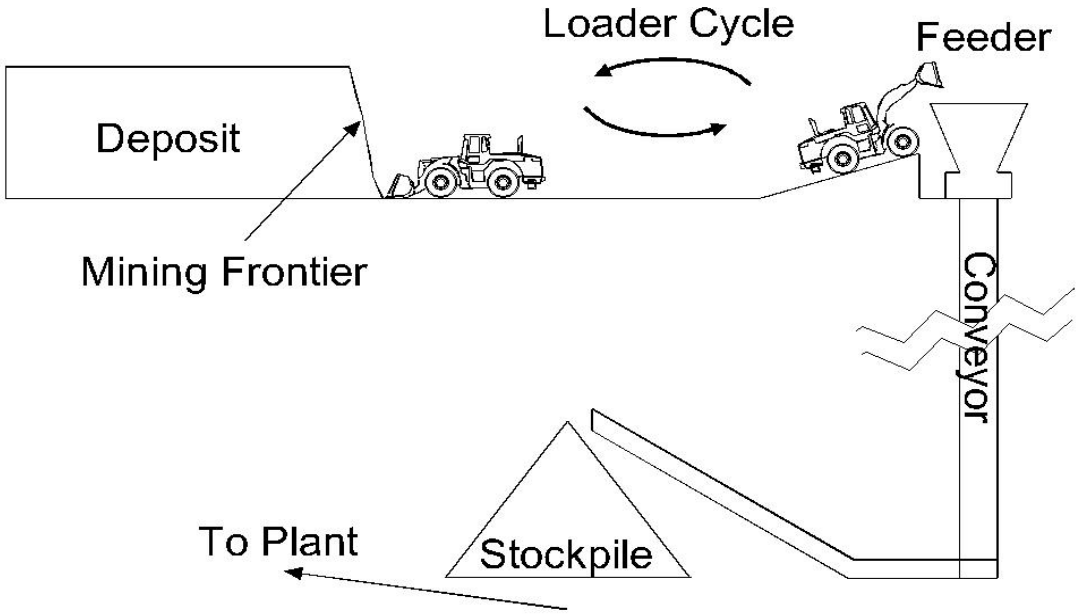
The Mine

- Open pit aggregate mine
- Contains sand, gravel, cobble and boulders
- Consists of millions of tons of sand, gravel and granite
- Prior ownership left the deposit partially mined.

The Operation

- Three loaders excavate and transport aggregate to a feeder.
- The feeder releases the aggregate onto a conveyor belt.
- The conveyor belt transports the aggregate to a stockpile, and then subsequently to a plant.
- The plant sorts the aggregate using gravity and agitation into piles based on granularity.

Depiction of Operation



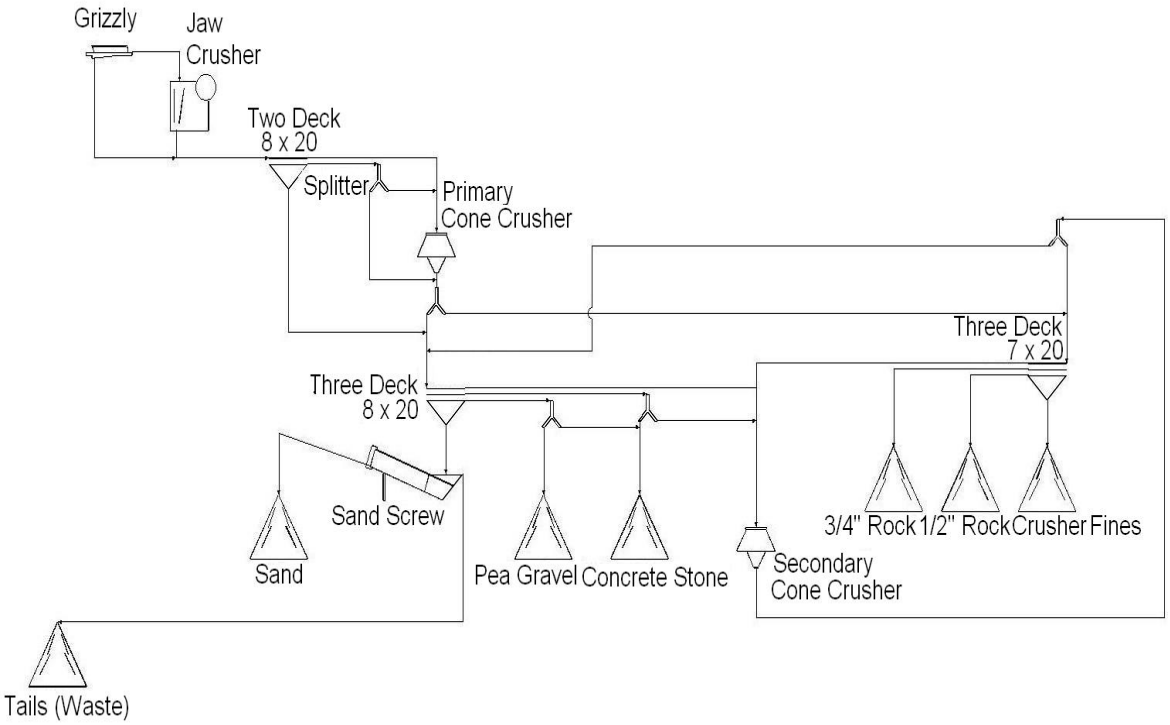
A Loader

The Conveyor Belts

The Products

- Sand, pea gravel, concrete stone, and rock are used to produce concrete and asphalt.
- Crusher fines and sand are used for structural fills and beddings.
- Cobble is used for erosion control in building developments.
- Boulders are used as landscaping materials.

The Plant


Grizzly
Jaw
Crusher
Two Deck
8 x 20
Splitter
Primary
Cone Crusher
Three Deck
7 x 20
Three Deck
8 x 20
Sand Screw
Sand
Pea Gravel
Concrete Stone
3/4" Rock
1/2" Rock
Crusher Fines
Secondary
Cone Crusher
Tails (Waste)

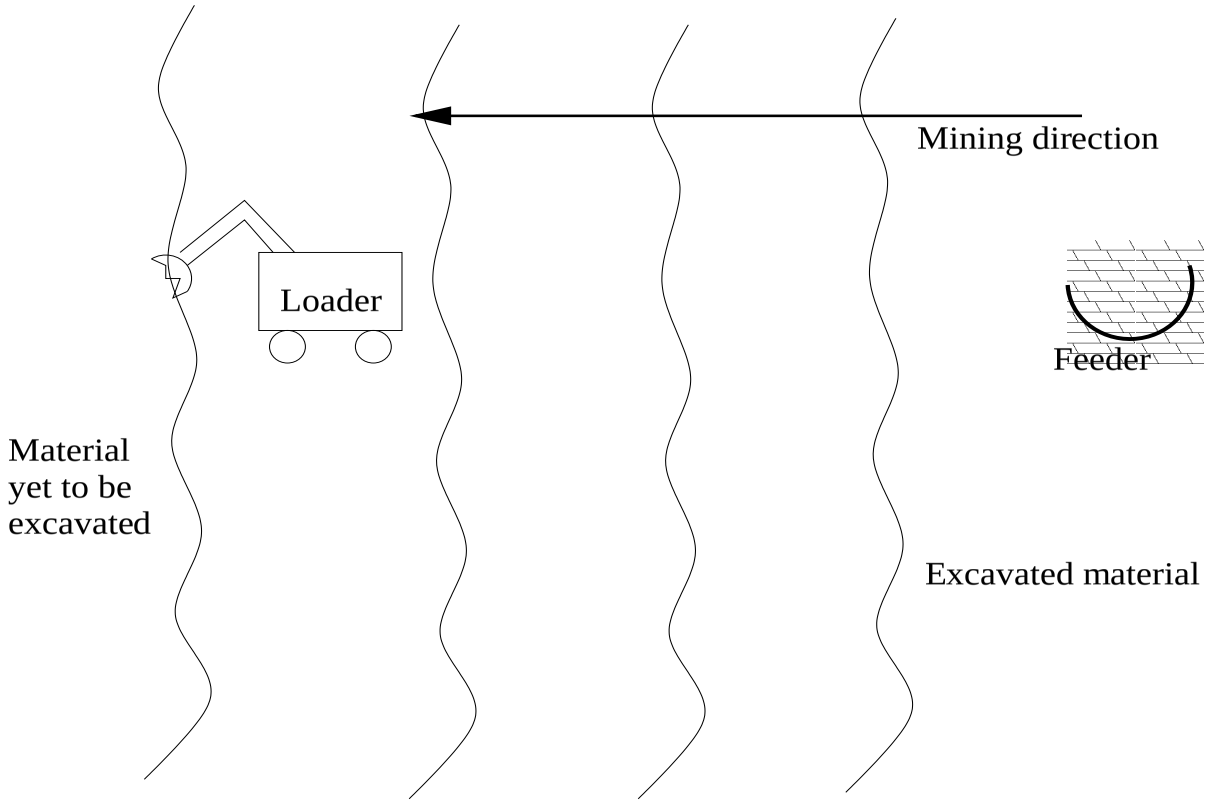
Economic Analysis

- Before an aggregate mine becomes operational, economic analysts use geographic sampling, expected operational costs and market information to determine whether the mine is likely to be profitable.
- Fixed costs: depreciation, exploration and development, permitting, insurance, salaried employees, equipment, rail line on the property
- Variable costs: wages for hourly employees, supplies, loader fuel, utilities, stripping

Current *Modus Operandi*

- Mine managers place the feeder in an “intuitive” centralized location.
- Loaders run from the excavation site to the feeder.
- Mine managers add loader hours as the travel distance between the feeder and the excavation site increases.
- Eventually production requirements cannot be met.

Problem with *Modus Operandi*



Moving the Feeder

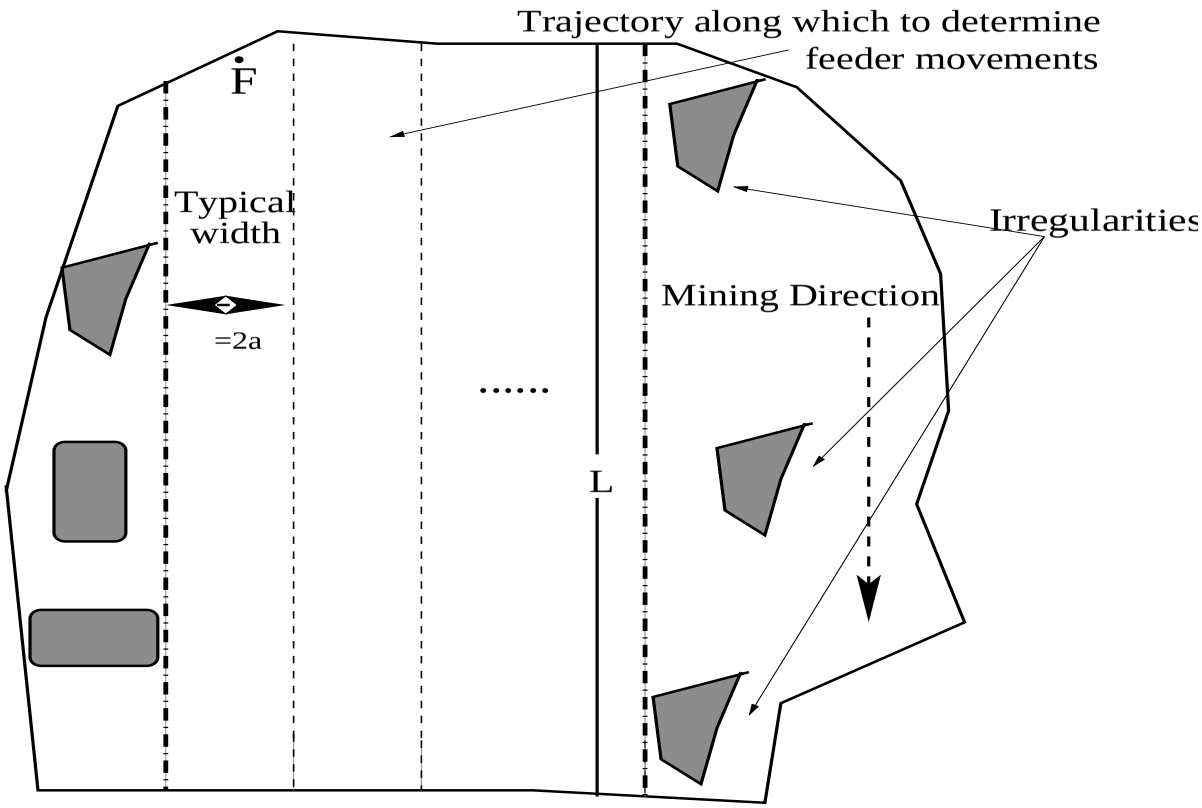
- The mining operations must cease while the feeder is moved.
- The feeder is moved from its current location with conveyor belt extensions.
- **Problem:**
  - There is no advance warning of feeder movements.
  - The feeder must often be moved at inopportune times.
  - This feeder policy overtaxes loaders and precludes synchronizing moves with downtime at the plant.
  - The sequence of feeder moves is suboptimal.

Literature Review

- Ultimate pit limit problem (assumes of a certain production rate and cutoff grade): Underwood and Tolwinski (1998), Hochbaum (2001)
- Open pit production scheduling: Caccetta and Hill (2003)
- Underground mine scheduling: Carlyle and Eaves (2001), Kuchta *et al.* (2004)

Initial Model Conditions

Place the feeder initially using geometric considerations



Model Idea

- We need to determine when to move the feeder, and to what location, balancing the cost of a feeder movement with the cost of excavation (long cycle times).
- Assumptions:
  - The initial feeder position is known.
  - The trajectory area is regular and of fixed width.
  - The aggregate is homogeneous and of fixed depth.

Shortest Path Model

- i, j = y-coordinate of feeder along a trajectory
- N = all allowable instances of i (e.g., $\{0, 20, 40\}$)
- A = all allowable (i, j) pairs (e.g., $\{(0, 20),\ (20, 40)\}$)
- f = fixed cost of moving the feeder
- v_{ij} = variable cost of moving the feeder from i to j

$$x_{ij} = \begin{cases} 1 \text{ if we move the feeder from } i \text{ to } j \\ 0 \text{ otherwise} \end{cases}$$

Shortest Path Model: Algebra

Objective

$$\min \sum_{i,j} (f + v_{ij}) x_{ij}$$

Constraints

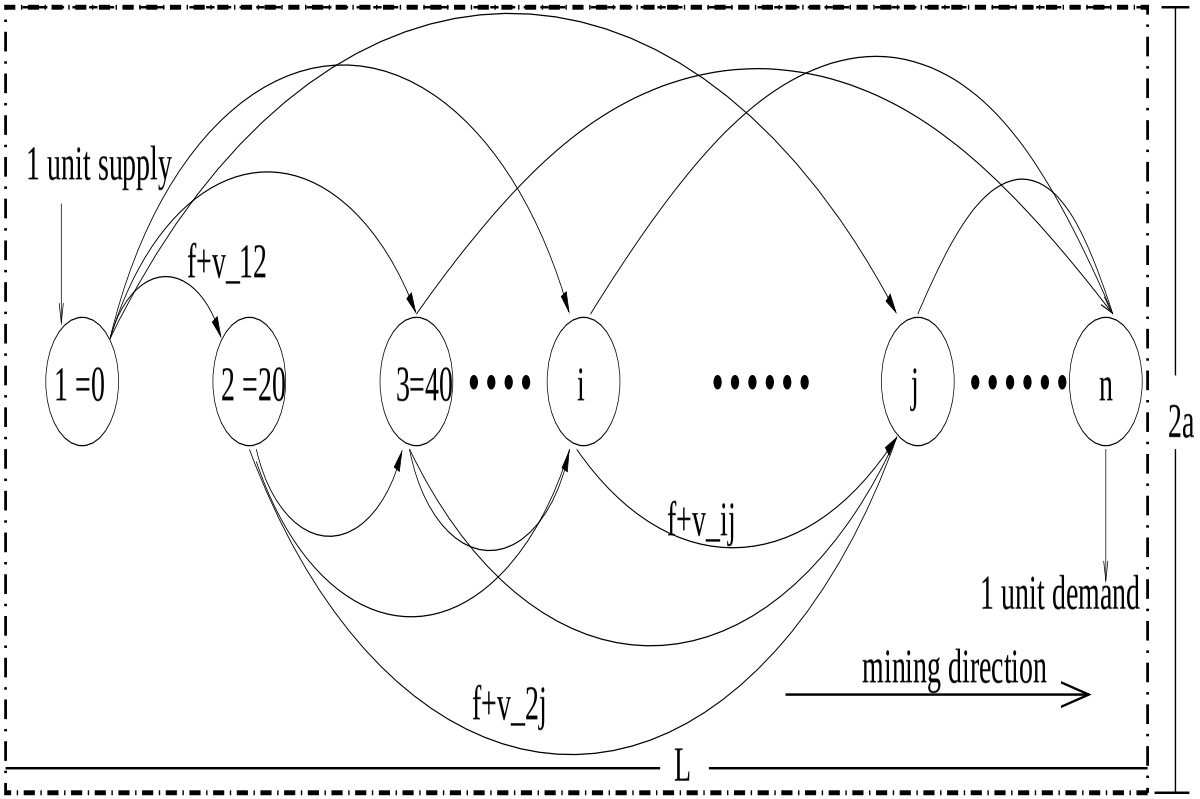
$$1 = \sum_{j} x_{1j}$$

$$\sum_{i} x_{ij} = \sum_{k} x_{jk} \quad \forall j \in A, j \neq 1, n$$

$$\sum_{i} x_{in} = 1$$

$$0 \leq x_{ij} \leq 1 \quad \forall (i,j) \in A$$

Shortest Path Model: Topology



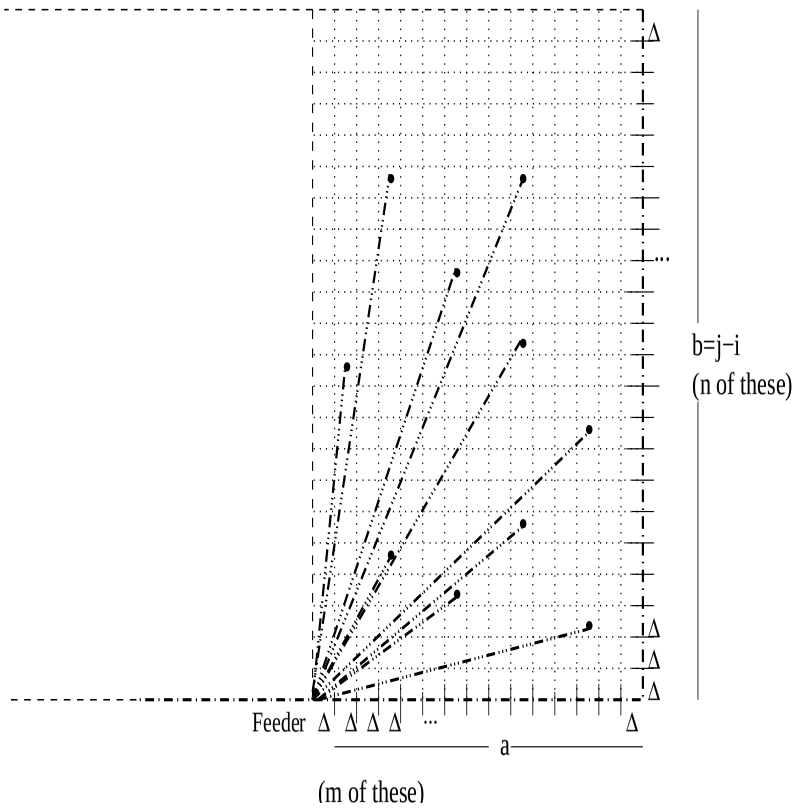
Cost Data

- fixed cost
  - production loss
  - extra equipment
- variable cost
  - labor cost
  - loader fuel
  - loader maintenance

Computing the Variable Cost

- Approximate the number of feet a loader moves on average between i and j within a rectangle with length j-i and a width $2a$ (or a).
- Compute the cycle time based on distance.
- Compute the number of loaders needed to meet production requirements based on the cycle time and loader capacity.
- Compute the cost for the loaders to run.

Deriving the Average Haul Distance for a Loader



$(i\Delta + \Delta/2, j\Delta + \Delta/2)$, $i = 0, ..., m-1$ and $j = 0, ..., n-1$ gives the $x-$ and $y-$coordinates, respectively, of the center of any small square within the $a \times b$ rectangle.

The distance between the feeder and the center of an arbitrary square is:

$$\sqrt{\Delta^2(0.5+i)^2 + \Delta^2(0.5+j)^2}$$

The average distance across all such squares is:

$$1/(nm) \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \sqrt{\Delta^2(0.5+i)^2 + \Delta^2(0.5+j)^2}$$

$$= 1/(nm) \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \sqrt{a^2(0.5+i)^2/m^2 + b^2(0.5+j)^2/n^2}$$

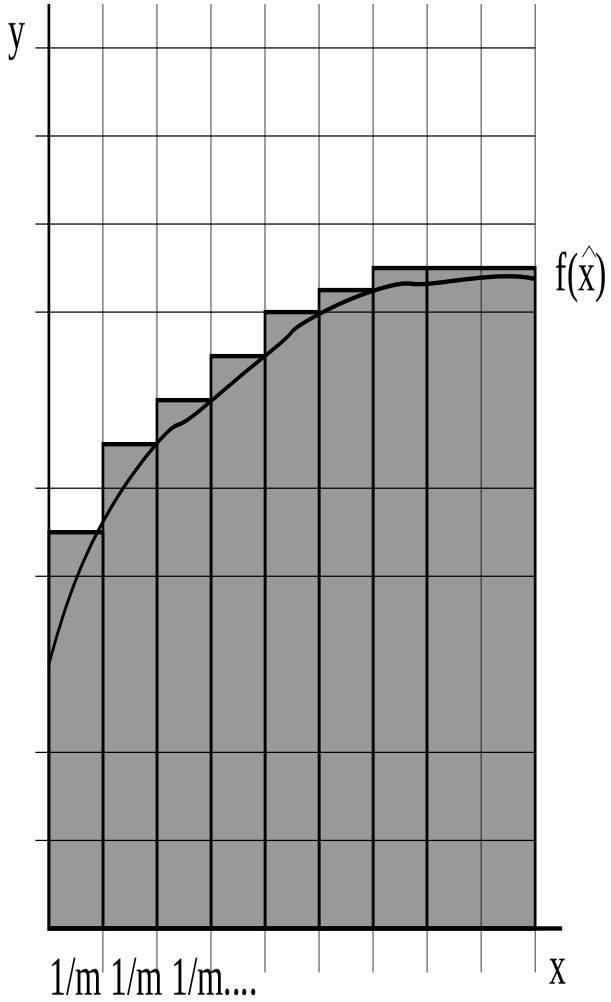
(because $\Delta = \frac{a}{m} = \frac{b}{n}$)

Holding the second variable corresponding to the j index fixed, and using c as a constant representing the corresponding term, we note that:

$$\frac{1}{m}\sum_{i=0}^{m-1}\sqrt{a^2((0.5+i)/m)^2+c^2}$$

is a Riemann's sum with length $1/m$ and height $f(x)=\sqrt{a^2((0.5+i)/m)^2+c^2}$.

Riemann's sum



Recall $\hat{x}_i = \Delta(0.5 + i) = \frac{a}{m}(0.5 + i)$; so, if we let $x_i = \frac{0.5+i}{m}$, we scale by a.

So, as $m \to \infty$, we can approximate the sum with the following integral:

$$\int_0^1 \sqrt{a^2x^2 + c^2}dx$$

(Limits of integration follow from: $x_i = \frac{0.5+i}{m}$, and when $i = 0$, $x_i \approx 0$; when $i = m - 1$, $x_i \approx \frac{m-1}{m} = 1$ as $m \to \infty$.)

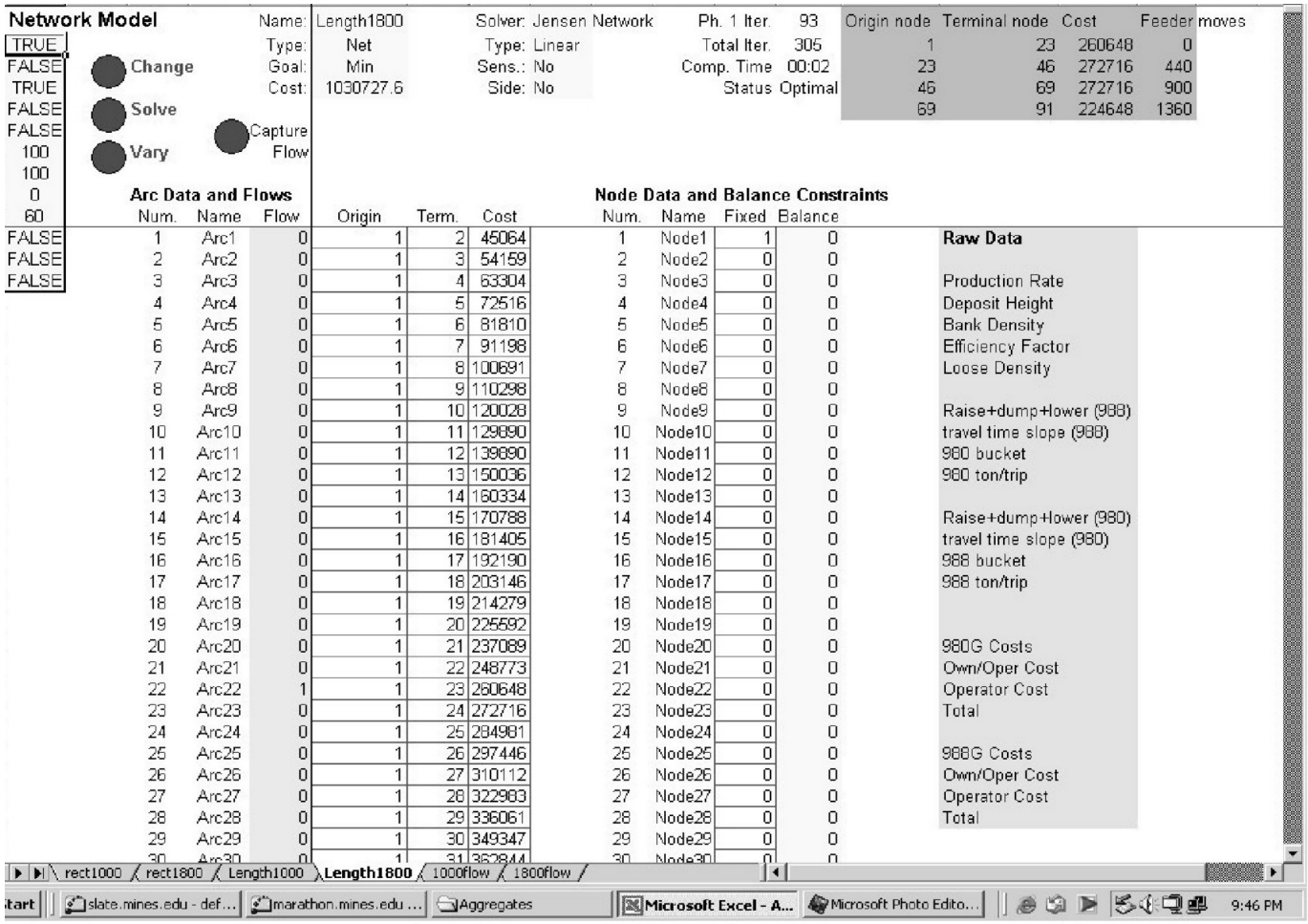
Letting y also vary, the expression for the average distance across all such squares can be approximated:

$$\int_0^1 \int_0^1 \sqrt{a^2x^2 + b^2y^2}dxdy$$

which can be integrated via u-substitution and a transformation to polar coordinates to yield:

$$1/3(\sqrt{a^2+b^2} + \frac{a^2}{2b}\ln(\frac{a+b+\sqrt{a^2+b^2}}{a-b+\sqrt{a^2+b^2}}) - \frac{b^2}{2a}\ln(\frac{b}{a+\sqrt{a^2+b^2}}))$$

Excel and the Jensen solver



Network Model

Name:	Length1800	Solver:	Jensen Network	Ph. 1 Iter.	93	Origin node	Terminal node	Cost	Feeder moves
Type:	Net	Type:	Linear	Total Iter.	305	1	23	260648	0
Goal:	Min	Sens.:	No	Comp. Time	00:02	23	46	272716	440
Cost:	1030727.6	Side:	No	Status	Optimal	46	69	272716	900
						69	91	224648	1360

TRUE
FALSE — Change
TRUE
FALSE — Solve
FALSE — Capture Flow
100 — Vary
100
0
60

Arc Data and Flows

	Num.	Name	Flow	Origin	Term.	Cost
FALSE	1	Arc1	0	1	2	45064
FALSE	2	Arc2	0	1	3	54159
FALSE	3	Arc3	0	1	4	63304
	4	Arc4	0	1	5	72516
	5	Arc5	0	1	6	81810
	6	Arc6	0	1	7	91198
	7	Arc7	0	1	8	100691
	8	Arc8	0	1	9	110298
	9	Arc9	0	1	10	120028
	10	Arc10	0	1	11	129890
	11	Arc11	0	1	12	139890
	12	Arc12	0	1	13	150036
	13	Arc13	0	1	14	160334
	14	Arc14	0	1	15	170788
	15	Arc15	0	1	16	181405
	16	Arc16	0	1	17	192190
	17	Arc17	0	1	18	203146
	18	Arc18	0	1	19	214279
	19	Arc19	0	1	20	225592
	20	Arc20	0	1	21	237089
	21	Arc21	0	1	22	248773
	22	Arc22	1	1	23	260648
	23	Arc23	0	1	24	272716
	24	Arc24	0	1	25	284981
	25	Arc25	0	1	26	297446
	26	Arc26	0	1	27	310112
	27	Arc27	0	1	28	322983
	28	Arc28	0	1	29	336061
	29	Arc29	0	1	30	349347
	30	Arc30	0	1	31	362844

Node Data and Balance Constraints

Num.	Name	Fixed	Balance
1	Node1	1	0
2	Node2	0	0
3	Node3	0	0
4	Node4	0	0
5	Node5	0	0
6	Node6	0	0
7	Node7	0	0
8	Node8	0	0
9	Node9	0	0
10	Node10	0	0
11	Node11	0	0
12	Node12	0	0
13	Node13	0	0
14	Node14	0	0
15	Node15	0	0
16	Node16	0	0
17	Node17	0	0
18	Node18	0	0
19	Node19	0	0
20	Node20	0	0
21	Node21	0	0
22	Node22	0	0
23	Node23	0	0
24	Node24	0	0
25	Node25	0	0
26	Node26	0	0
27	Node27	0	0
28	Node28	0	0
29	Node29	0	0
30	Node30	0	0

Raw Data

Production Rate
Deposit Height
Bank Density
Efficiency Factor
Loose Density

Raise+dump+Hower (988)
travel time slope (988)
980 bucket
980 ton/trip

Raise+dump+Hower (980)
travel time slope (980)
988 bucket
988 ton/trip

980G Costs
Own/Oper Cost
Operator Cost
Total

988G Costs
Own/Oper Cost
Operator Cost
Total

rect1000 / rect1800 / Length1000 / **Length1800** / 1000flow / 1800flow

start | slate.mines.edu - def... | marathon.mines.edu ... | Aggregates | Microsoft Excel - A... | Microsoft Photo Edito... | 9:46 PM

Results

- The two Parkdale deposits are $1800'$ and $1000'$ in length, and both are $1200'$ in width.
- We compute the optimal trajectory moves and the associated total cost of mining the deposit for widths of $100'$, $200'$, $300'$, $400'$, $600'$, and $1200'$.
- For the $1800'$ length deposit, optimal feeder moves are spaced either $440'$ or $460'$ apart, and occur along a trajectory width of $1200'$.
- For the $1000'$ length deposit, move the feeder once to $500'$ along a trajectory width of $1200'$.

Cost Comparison

- Optimal moves are 13%-14% lower cost than that obtained with the *modus operandi*.
- These percentages are actually lower bounds on the cost savings because:
  - (i) we assume that the mine would choose the optimal trajectory width while determining feeder moves without our model
  - (ii) we do not consider the detrimental effects of poor loader maintenance schedules, lack of coordination between feeder movements and scheduled downtime at the plant, and low customer satisfaction.

Quote from General Manager (Tom Maul)

“Traditionally, mine managers... defer... the effort of [planning pit feeder movements] until absolutely necessary... [because] many aggregate mines exist on a scale that does not justify a management team... a single person... does not have... time to perform lengthy optimization analyses.

The underlying... assumptions that provide the basis for the development of this optimization model are sound, and the results are very credible. This model represents a practical management tool for the aggregates industry, and it is our intent to apply the model.”