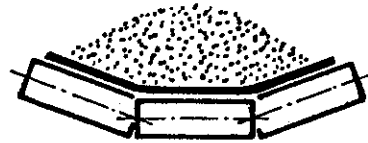


BELTCON 1



BELT CONVEYORS - DESIGN, OPERATION AND OPTIMIZATION

PAPER B1

A COMPARISON OF OVERLAND CONVEYING SYSTEMS

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I - Introduction. A cost comparison among various modes of transporting minerals and coal is sensitive to the transportation configuration, i.e., location, transport distance, and the number of terminals; annual tonnage; the size of shipment; the design parameters, i.e., among others, the characteristics of raw materials and the users specification; and the methods of accounting. To be realistic, the conditions under which the comparison is made should be identical for all modes. Thus, for instance, if the user requirement necessitates crushing of the material to a fine consistency, the cost of pre-sizing in the slurrification plant should not be included in the comparison.

When a bulky material is to be transported between two points, the shipper has a choice of selecting among the following modes of transport or an appropriate combination thereof: truck, rail, freight pipelines (slurry, pneumatic, and capsule pipelines), conveyor belts, and sometimes barges and ocean going vessels.

Whenever these facilities exist the proper method of cost estimation would be to contact the operating companies involved. However, if there is a need to construct a new facility or to extend the one that already exist, a component analysis would be the most accurate way the estimate can be developed. Such a component analysis would include capital, operating, and maintenance costs of each component of the system:

$$C = \sum_{i=1}^n C_i F_i + \sum_{i=1}^n O_i \quad (1)$$

where C = the total annual cost of the system in dollars, n = the number of components, C_i = capital cost of i -th component in dollars, O_i = operation and maintenance cost of i -th component in dollars per year, r = annual interest rate ($0 < r < 1.0$) [0.06]*, F_i = capital recovery factor equal to $\frac{r}{1 - (1+r)^{-n_i}}$, n_i = life span associated with i -th component in years, and i = index for counting cost components.**

The structure of the cost model for slurry pipeline, pneumo-capsule pipeline,** rail, and truck is shown in Figures 1, 2, 3, and 4 respectively.

The annualized cost per ton-mile in dollars, C_t^a , can be written as:

$$C_t^a = \frac{C}{QL_M} \quad (2)$$

where Q = the annual freight transported in tons per year, and L_M = the transport distance in miles [300].

The cost estimated according to Equation (2) is composed of two components: fixed and variable. While the fixed cost remains constant, the variable cost changes with time. A more comprehensive cost estimation may be made by evaluating the present value of the total cost over the life span of the coal pipeline. In this procedure the variable cost needs to be increased annually to account for inflation. Subsequently, future annual cost must be discounted to represent the present value of future expenditures. The summation of these inflated-discounted costs represents the project's present value. This statement can be formulated as:

$$C_t^P = \frac{\sum_{i=1}^n C_i + \sum_{T=0}^N \sum_{i=1}^n O_i \left(\frac{1+r'}{1+d}\right)^T + 2r \sum_{i=1}^n C_i}{L_M \sum_{T=0}^N Q(1+e)^T} \quad (3)$$

* Numbers in [] refer to numerical values in calculating costs shown in Figure 1, see Comparison. Note that the values of financial parameters were selected for the comparison with OTA study.

** Note that equation 1 assumes zero salvage value.

where C_t^P = the project's present value in dollars per ton-mile,* r' = the rate of inflation [.06], d = the discount rate [.12], r = the interest rate [.06]**
 N = life span of the project in years [20], e = the annual rate of freight increase [.03], and T = index for counting years of operation.

The present paper discusses the cost model for slurry pipeline. The cost models for rail⁽¹⁾, truck⁽¹⁾, and capsule pipelines⁽²⁾ are described elsewhere. The cost models for barges, conveyor belts, and pneumatic pipeline are under development.

*If components of the project have different life spans the, the term

$$\sum_{i=1}^n C_i, \text{ in equation (3) must be replaced by } \sum_{i=1}^n C_i + \left[\sum_{T=0}^{T=N_1} \left(\sum_{j=1}^n C_j \right) (1+r')^T \right] \left(\frac{1}{1+d} \right)^{N_1} + \left[\sum_{T=0}^{T=N_2} \left(\sum_{k=1}^{n_2} C_k \right) (1+r')^T \right] \left(\frac{1}{1+d} \right)^{\dots}, \text{ where } N_1 \text{ and } N_2 \text{ are the life spans in}$$

years of n_1 and n_2 components of the system. It is assumed that no major component of the system will be replaced more than once in the life of the project and also all components inflate at the same rate. If further refinements need to be included, the replacement term becomes more complicated. Such complication is not warranted for preliminary evaluation of a pipeline project.

**It is assumed that the capital will be needed in three successive years during the construction phase of the project.

II - Slurry Pipeline System - A slurry pipeline system is composed of the following major components: slurrification plant, pipeline, pump stations, communication system, and dewatering plant. In a typical plant such as Black Mesa, coal entering the system first is crushed, dry, in cage-paktor crushers to a ½ inch X 0 inch size and then by wet grinding in rod-mills, to below 8 mesh (.093 inches) size. Slurry thus produced in rod-mills, is delivered into holding tanks prior to being pumped 273 miles in an 18 inch pipeline to Mohave generating station. Four pumping stations along the line provide the required energy for the transport. At the Mohave dewatering plant the slurry is stored in agitated tanks prior to being passed through a series of Dynacone centrifuges to separate the water from the coal. The moist coal is sent to pulverizers where it is dried with hot air and fed to the furnaces while the supernatant is treated through clariflocculators. (3)

While future slurry pipeline systems may be designed somewhat differently than the Mesa pipeline, the differences will not be extensive. Future improvements in facilities and equipments are bound to reduce cost in constant dollar rather than increase them. Therefore, a cost estimate based on Black Mesa pipeline design may be treated as a conservative estimate and used with reasonable confidence in feasibility studies. Thus, in development of the cost model which follows, first a design, similar, in its major components, with Black Mesa pipeline system was assumed and then the cost of each component was formulated. Subsequently, these cost formulae were incorporated via the use of equation (2) or equation (3) into a pipeline system cost model. Equation (2) may be used when the annualized cost is of interest and equation (3) when the project's present value is needed.

In costing the equipments, the following "type formula" was used for scale-up:

$$C_m = C_n \left(\frac{q_m}{q_n} \right)^\alpha \quad (4)$$

where C_m = the installed cost in dollars of a given equipment of the capacity q_m in T/h, C_n = the installed cost in dollars of the same equipment of the capacity q_n in T/h, α = a scale up power having a value between 0 and 1.

This formulation allows the estimation of the cost of various sizes of a given

equipment when the cost of a single unit, of the same type, is known. In developments that will follow, we will assume that C_n for a given equipment of capacity q_n is known in a given base year. When the unit used is the same unit for which the cost of installation is known then, $C_m = C_n$.

A - Capital Cost

1 - Slurrification Plant - Coal reaching slurrification plant normally consists of lumps smaller than 2 inches. This coal enters first the cage-paktor and is crushed to minus $\frac{1}{2}$ inch and then into the rod-mill where slurry is formed for pumping. The major components of a slurrification plant are cage-paktor, rod-mills, storage tanks and mixer. In addition, there are other equipments such as conveyer belts, piping, and circulating pumps.

a - Cage-paktor - This equipment crushes coal lumps by propelling them against solid surfaces at a proper velocity. The installed cost of a unit cage-paktor can be written as:

$$C_{cu} = C_{bu} + C_{fu} + C_{mu} + C_{su} + C_{iu} \quad (5)$$

where C_{cu} = the installed cost of a unit of cage-paktor with the capacity q_u T/h, C_{bu} = the unit's base price, C_{fu} = the cost of freight and handling, C_{mu} = the cost of motor control and instrumentation, C_{su} = the cost of foundation and support, and C_{iu} = the installation costs all in dollars per unit.

The total cost of cage-paktor installation for a slurrification plant which uses N units, each having a capacity q_u , is:

$$C_{cage} = (N + a) C_{cu} I_N \quad (6)$$

where C_{cage} = the total cost of N cage-paktor installation in dollars, a = the number of standby cage-paktors, I_N = the Engineering News Record Cost Index ratio* (1977) [1].

Using the formulation of Equation (4) we can write:

*In this paper cost indexes are given as a ratio of the index at the design year to the index at a base year. The base years are shown in () after each index.

$$C_{\text{cage}} = (N + a) C_n \left(\frac{q_u}{q_n}\right)^a I_N \quad (7)$$

where $N = \left(\frac{Q}{24 D_{\text{op}} q_u}\right)_r$ rounded to its nearest integer, as shown by subscript r .

The knowledge of the installed cost of a cage-paktor of capacity q_n , allows the estimate of the installed cost of cage-paktors needed for a system using units of the size q_u .

In 1977 Bernstrom⁽⁴⁾ estimated the installed cost of six 300-tons-per-hour cage-paktor units for a 10,000,000 ton per year coal slurrification plant in dollars. This estimate is shown in Table 1.

Table 1 - Breakdown of Cost of Installation of Cage-Paktors (75") 1977, in Dollars

	Six Units each having 300 T/h capacity	One Unit of $q_n =$ 300 T/h capacity
Base price	1,060,000	$C_{bn} = 176,666=180,000$
Motor Control & Instruments	365,000	$C_{mn} = 60,833= 61,000$
Foundation & Support	60,000	$C_{sn} = 10,000= 10,000$
Installation	60,000	$C_{in} = 10,000= 10,000$
Freight & Handling	110,000	$C_{fn} = 18,333= 20,000$
	<u>\$1,705,000</u>	$C_n = \underline{275,832=281,000}$

The C_n column has been estimated by simple proportioning. If plants of larger capacities use multiples of 300 T/h units (Black Mesa pipeline uses three) then $q_u = q_n$ and equation (7) becomes:

$$C_{\text{cage}} = \left[\left(\frac{Q}{24 D_{\text{op}} q_n}\right)_r + a \right] C_n I_N \quad (8)$$

where $C_n = 310,000$ \$/Unit* of 300 T/h 75" cage-paktor installed, $a =$ one or two (in Black Mesa it is one), and $I_N = 1$ for 1977.

b - Rod Mill - In the rod mill, the coal sizes are further reduced by wet grinding to acceptable distribution for pipe transport.

The installed cost of a unit of rod-mill, can be written as:

$$C_{ru} = C'_{bu} + C'_{cu} + C'_{fu} + C'_{su} + C'_{iu} + C'_{ru} + C'_{eu} \quad (9)$$

where C'_{ru} = the installed cost of a unit of rod-mill with the capacity q'_u , T/h, C'_{bu} = the units' base price, C'_{cu} = the cost of motor control and instrumentation, C'_{fu} = the freight and handling charges, C'_{su} = the cost of foundation and support, C'_{iu} = the installation cost, C'_{ru} = the cost of initial rod charges, and C'_{eu} = the building cost, all in dollars per unit.

The total cost of rod-mill installation for a slurrification plant which uses N' units, each having a capacity q'_u in T/h is:

$$C_{rod} = (N' + b)C_{ru} I_N \quad (10)$$

Following the formulation of Equation (7) we can write:

$$C_{rod} = \left[(N' + b)C'_n \left(\frac{q'_u}{q'_n}\right)^\beta + C'_{rc} \right] I_N \quad (11)$$

where C_{rod} = the installed cost of rod-mills installation in dollars, C'_n = the installed cost (known) of a rod-mill with capacity q'_n T/h in dollars per unit, β = the scale-up power, C'_{rc} = the cost of a rod-charging facility in dollars per unit

In 1977 Bernstrom⁽⁴⁾ presented a cost estimate for rod-mill installation based on 6 units of 300 T/h capacity. This breakdown is shown in Table 2

*A 10 per cent miscellaneous cost was assumed.

Table 2 - Breakdown of Cost of Installation of (13' X 18') Rod-Mills in dollars (1977)

	<u>Six Units each having 300 T/h capacity</u>	<u>One unit of $q_n=300$ T/h capacity</u>
Base Price	4,060,000	$C'_{bn} = 676,666 = 700,000$
Motor Control & Instruments	665,000	$C'_{cn} = 110,833 = 111,000$
Freight & Handling	290,000	$C'_{fn} = 48,333 = 48,000$
Foundation & Support	270,000	$C'_{sn} = 45,000 = 45,000$
Installation	230,000	$C'_{jn} = 38,333 = 40,000$
Initial Rod Charge	190,000	$C'_{rn} = 31,666 = 32,000$
Equalized building	<u>110,000</u>	$C'_{en} = \underline{18,333} = \underline{20,000}$
	\$ 5,815,000	$C'_n = 969,164 = 996,000$
Rod Charger Machine		$C'_{rc} = \quad = 35,000$

Assuming that through-put warrants the multiple use of the 300T/h unit, then $q'_u = q'_n$ and equation 11 can be written as:

$$C'_{rod} = \left\{ \left[\left(\frac{Q}{240 \cdot op \cdot q_n \cdot r} \right) + b \right] C'_n + C'_{rc} \right\} I_N \quad (12)$$

where $C'_n = 996,000 \times 1.1^*$ dollars per unit of 300 T/h (13' X 18' Rod-Mills installed), $b =$ one or two (in Black Mesa pipeline it is one) [1], $C'_{rc} = 35,000$ in dollars per unit, and $I_N =$ one for 1977.

c - Storage and Mixing - A few hours of slurry storage at the slurrification plant must be provided. To maintain the consistency of the slurry it should be kept uniform by mixing. The volume of storage in cubic feet at the slurrification plant, S_s , can be written as:

*[1] is a coefficient taking account of miscellaneous costs.

$$S_s = \frac{\overline{V}_s t_s}{D_{op}} = \frac{\left(\frac{W_s}{\gamma_s}\right) t_s}{D_{op}} = \frac{\left(\frac{2000Q_c}{C_c}\right) t_s}{\gamma_s D_{op}} \quad (13)$$

where t_s = the duration of storage in days and may vary between .4 and .8*,
 \overline{V}_s = the volume of slurry in cubic feet per year, W_s = the weight of slurry in pounds per year, Q_c = the weight of dry coal in tons per year, C_c = the concentration by weight of coal in slurry in fraction [.48], and γ_s = the specific weight of slurry in pounds per cubic foot and is equal to:

$$\gamma_s = \frac{1}{\frac{C_c}{\gamma_c} + \frac{(1 - C_c)}{\gamma_w}} \quad (14)$$

where γ_c = the specific weight of coal in lb/ft³ [1.41 x 62.4], and
 γ_w = the specific weight of water in lb/ft³ [62.4].

Cost of storage and mixing can be formulated as follows:

$$C_{st} = C_{stu} S_s I_N \quad (15)$$

$$C_{mi} = C_{miu} S_s I_N \quad (16)$$

where C_{st} = the cost of storage in dollars, C_{stu} = the cost of storage per cubic foot of storage in dollars [.8], C_{mi} = the cost of mixing in dollars, C_{miu} = the cost of mixing per cubic foot of storage in dollars [.3].

In fact, C_{stu} and C_{miu} are both functions of the storage capacity. However, the relative amount, compared with the cost of other components, are so small that the assumption of constant values will not introduce too great an approximation.

*At Black Mesa slurrification plant four tanks, each with dimensions of 49' diameter by 45' height provide storage for a transport system of 370 tons per hour of coal.

d - Cost of slurrification plant - In addition to the above major components, a typical slurrification plant includes raw coal bins, conveyer belts, cyclone classifier, distributor, and pumps. All these are small and uncomplicated mechanical systems and can be cost evaluated individually if it is so desired. However, for the feasibility study it is sufficient to add a certain percentage to the costs of other components to take care of these items. Therefore, the cost of slurrification plant C_{s1} , in dollars can be written as:

$$C_{s1} = \{C_{cage} + C_{rod} + C_{st} + C_{mi}\} (1 + \theta) I_N \quad (17)$$

where θ = the coefficient for miscellaneous costs [.1].

Using equations 8, 12, 15, 16, and 17 one can write:

$$C_{s1} = \left\{ \left[\left(\frac{Q}{24D_{op} q_n} \right)_r + a \right] C_n + \left[\left(\frac{Q}{24D_{op} q'_n} \right)_r + b \right] C'_n + C'_{rc} + (C_{stu} + C_{miu}) S_s \right\} I_N \quad (18)$$

Noting that $Q = (1 + W)Q_c$, where W = the moisture content of coal as it arrives at the slurrification plant in fraction [.08], and substitution from previous equations will yield:

$$C_{s1} = \left\{ \left[\frac{Q_c (1 + W)}{24D_{op} q_n} \right]_r (C_n + C'_n) + a C_n + b C'_n + C'_{rc} + (C_{stu} + C_{miu}) \right\} I_N (1 + \theta) \quad (19)$$

$$\left(\frac{2000 t_s Q_c [C_c \gamma_w + (1 - C_c) \gamma_c]}{C_c \gamma_c \gamma_w D_{op}} \right) I_N (1 + \theta)$$

2 - Pipeline - The cost of Cross Country line-haul in dollars, C_c , can be written as:

$$C_c = [(P_M + P_I + P_W) (L_c - L_r) + P_r L_r] (1 + \xi_c) \quad (20)$$

where P_M = the cost in dollars per lineal foot of pipe delivered at the site, P_I = the cost in dollars per lineal foot of installation, P_W = the cost in dollars per lineal foot of right-of-way, L_c = the total length of cross-country pipeline in feet including river crossings [1425600], L_r = the length of river crossings in feet [15840], P_r = the cost of river crossing in dollars per lineal foot of crossing, and ξ_c = a coefficient for miscellaneous costs [.01].

The following equations have been developed elsewhere: ⁽²⁾

$$P_M = 215DtI_m \quad (21)$$

where I_m = a ratio incorporating the pipeline price change with year 1973 [1.43]*, D = the inside diameter of pipe in feet, and t = the thickness of the pipe in feet [.03].

Installation cost is given as: ⁽²⁾

$$P_I = 0.040W^{.92} P_d^{1.1} I_i \quad (22)$$

where W = the wage rate factor which is a ratio of average annual wage rate in the geographic location under consideration over the average annual national wage rate [1.021], P_d = the population density in persons per square mile [265], I_i = the ratio of ICC pipeline construction index for the design year over the same index for the base year (1973) [14].

*See reference (8) for more information. The ratio can be approximated by using whole sale price index.

The right of way cost was found to be ():

$$P_w = 0.04P_d I_f \quad (23)$$

where I_f = the ratio of the Farm Real Estate Index for the design year over the same index for this study base year (1973) [1.0].

The Cost of River Crossing was given⁽⁵⁾:

$$P_r = .04DI_i L_r^6 \quad (24)$$

where I_i = the ratio of the ICC Pipeline Construction Index 1973 [], and L_r = the length of river crossing in feet.

therefore:

$$C_c = [(215Dt_m + 1700DW^{.92}P_d^{1.1}I_i + .04P_d I_f)(L_c - L_r) + .04DI_i L_r^{1.6}](T + \epsilon_c) \quad (25)$$

3 - Pumps - Long distance slurry pipelines are designed to maintain an intermediate regime. An accurate method of predicting energy losses in such a system has been proposed by E. Wasp⁽⁵⁾ and his co-workers at Bechtel, Inc. This methodology is comprehensively detailed and depends on many variables. However, if the designer wishes to create a system which operates in a similar regime as occurring in Black Mesa pipeline, J. Herbich⁽⁶⁾ has suggested a very simple calculation based on rheology of coal slurry of Black Mesa type. He suggested the use of Darcy-Weisbach head loss equation with a friction factor calculated from Moody diagram using the viscosity and density of slurry to calculate the Reynolds number. This simplifies the calculation considerably without loss of much accuracy.

The Darcy-Weisbach equation is :

$$h_f = \frac{\Delta p}{L} = \frac{f}{D} \frac{\gamma_s V^2}{2g} \quad (26)$$

where h_f = the pressure loss per lineal foot of pipeline in lbf/ft²/ft, Δp = the pressure loss in lbf/ft² for a distance of L ft, f = the friction factor [.0193], D = the inside diameter of pipe in ft. γ_s = the specific weight of slurry in lbf/ft³, V = the velocity of slurry in ft/sec [55], and g = the acceleration of gravity in ft/sec² [32.2].

Friction factor f can be evaluated from the Moody diagram using Reynolds number

$$N_{Re} = \frac{VD\rho_s}{\mu_s} \quad (27)$$

where ρ_s and μ_s are the density (slug/ft³), and viscosity of slurry. Herbich suggested that the relationship developed by Wasp and shown in figure 2 can be used as a basis of calculating μ_s . Horsepower required:

$$HP = \frac{h_f VAL_c}{550 \times .78} \quad (28)$$

where $.78$ = the efficiency of the pump, L_c = the length of pipe in ft, and A = the cross section of the pipe in ft².

The cost of pumping stations, C_{pump} , is proportional to the installed horsepower and can be written as:

$$C_{\text{pump}} = C_{pu} HP I_e = \frac{C_{pu} h_f VAL_c I_e}{550 \times .78} = \frac{C_{pu} f \gamma_s V^3 A L_c}{2g \times 550 \times .78} \quad (29)$$

where C_{pu} = the cost per one horse power installed in dollars [600], and I_e = ICC pipeline Cost Index Ratio (1976) [11].

4 - Communication - This cost is small and will be included in the miscellaneous capital cost.

5 - Dewatering plant - A typical dewatering plant is shown in Figure 1. It consists of a series of active storage tanks, centrifuges, pulverizers, clariflocculators, and a system of reslurrification of coal stored in inactive storage basins.

a - Storage tanks and Mixing - The active storage requirement of the dewatering plant is larger than that of the slurrification plant. It can be estimated from the following equation:

$$S_D = \frac{V_s}{D_{op}} t_D = \frac{2000 Q_c [C_c \gamma_w + (1 - C_c) \gamma_c]}{C_c \gamma_c \gamma_w} \times \frac{t_D}{D_{op}} \quad (30)$$

where S_D = the storage requirement in ft^3 , and t_D = the detention time in days [7].

A value of 4 to 7 days may be selected for t_D . Following formulation of equation 15 and 16 we can write:

$$C'_{st} = C_{stu} S_D I_N \quad (31)$$

$$C'_{mc} = C_{miu} S_s I_N \quad (32)$$

where C'_{st} = the cost of storage in dewatering plant in dollars, and C'_{mc} = the cost of mixers in the dewatering plant in dollars.

Combining equations 30, and 31, and 32, we find:

$$C'_{st} = \frac{2000 Q_c [C_c \gamma_w + (1 - C_c) \gamma_c]}{C_c \gamma_c \gamma_w} \times \frac{C_{stu} t_D I_N}{D_{op}} \quad (33)$$

$$C'_{mi} = \frac{2000 Q_c [C_c \gamma_w + (1 - C_c) \gamma_c]}{C_c \gamma_c \gamma_w} \times \frac{C_{miu} t_D I_N}{D_{op}} \quad (34)$$

b - Centrifuges and Pulverizers - In the first commercial coal slurry pipeline built in Ohio the disc filter was used to perform the dewatering function. At the later stage, however, they installed, for a period of one year and nine months, a Bird Solid Bowl Centrifuge on one of their pulverizing mills. The result, after a number of modifications proved to be successful. The Mohave dewatering plant of the Mesa pipeline uses exclusively centrifuges for dewatering. The slurry from the slurry tanks are pumped into a total of 20 Dynacone centrifuges, where it is dewatered. The coal cake then is conveyed to pulverizers where it is further dried and sent to furnaces.

The cost of centrifuges and pulverizers can be formulated as follows:

$$C_{cent} = (N_c + a'') C_n'' \left(\frac{q_u''}{q_n''} \right)^{\alpha'} I_N \quad (35)$$

$$C_{pul} = \left(\frac{N_c}{2} + a''' \right) C_n''' \left(\frac{q_u'''}{q_n'''} \right)^{\beta'} I_N \quad (36)$$

where $N_c = \left(\frac{\overline{V_s}}{24D_{op} q_n''} \right)$ = the number of centrifuges required, rounded to its nearest integer (Subscript r implies rounding operation), $\overline{V_s}$ = the volume of slurry in $ft^3/year$, C_n'' = the cost of a unit centrifuge having the capacity of $q_n'' ft^3/h$ [1600] in dollars (known at the base year) [230000], α' = the scale-up power, (varying between 0 and 1), a'' = the number of standby centrifuges [2], q_u'' = the capacity of the centrifuge selected in the design in ft^3/h [1600], C_{cent} = the total cost of centrifuges at the dewatering plant in dollars, C_{pul} = the total cost of pulverizers at the dewatering plant, a''' = the number of standby pulverizers [2], C_n''' = the cost of a unit of pulverizer having the capacity of $q_n''' T/h$ in dollars [30000], q_u''' = the capacity of pulverizer selected in the design in T/h [60] (q_n''' is solid content of $2 q_n''$), and β' = the scale-up power (varying between 0 and 1). When the unit used in the design is of the same capacity of the unit for which the prices are known then $q_u'' = q_n''$, $q_u''' = q_n'''$,

$$C_{cent} = (N_c + a'') C_n'' I_N = \left[\left(\frac{\overline{V_s}}{24D_{op} q_n''} \right)_r + a'' \right] C_n'' I_N \quad (37)$$

$$C_{pul} = \left(\frac{N_c}{2} + a''' \right) C_n''' I_N = \left[\left(\frac{\overline{V_s}}{24D_{op} q_n''} \right)_r + a''' \right] C_n''' I_N \quad (38)$$

c - Clariflocculators - Dynacone centrifuge's effluent still contains significant amounts of fine coal (about 8.5 per cent) and needs to be treated to make it suitable for discharge. The cost of clariflocculators in dollars, C_{cl} , can be formulated as:

$$C_{cl} = V_{cen} C_{clu} I_N \quad (39)$$

where $V_{cen} = \frac{2000 Q_c (1 - C_c)}{C_c D_{op} \times 7.48 \times 10^6}$ = approximately the flow of centrate in million gallon per day, and C_{clu} = the cost in dollars of treatment facility per million gallon capacity [72000]. Therefore:

$$C_{cl} = \frac{.26 Q_c (1 - C_c) 10^{-3}}{C_c D_{op}} C_{clu} I_N \quad (40)$$

d - Cost of dewatering plant - In addition to above major equipments a dewatering plant includes others. Halvorsen⁽⁷⁾ in 1976 presented a cost estimate for a centrifuge plant capable of handling 970 T/h coal (See Table 3).

Table 3 - Cost Breakdown for a Centrifuge Plant,
970 T/h (1976)

	<u>Cost in \$</u>	<u>% of Total</u>
Storage tanks 4-125" diam X 87'	8,960,000	24.9
Mixers	2,770,000	7.7
Charger pumps 6-14" ct (2 sp)	431,000	1.2
Effluent sump & pumps	79,000	.0
Centrifuges	8,400,000	23.3
Main Effluent Thickener 12-160'	550,000	1.5
Additional boiler cost	2,730,000	7.6
Piping	799,000	2.2
Foundation (no piling) & fill	973,000	2.7
Misc. structures	54,000	.0
Emergency pounds, 3 @ 115,000 tons ea.	777,000	2.1
Reclaim system	898,000	2.4
Misc. Electrical	1,848,000	5.1
Engineering profit contingency	<u>6,731,000</u>	<u>18.6</u>
		<u>100.00</u>

From Table 3 it can be seen that the cost of components calculated separately above comprises about 65% of the total. Therefore, the cost of dewatering plant can be written as:

$$C_{de} = \left\{ \frac{20000 C_c [C_c \gamma_w + (1 - C_c) \gamma_c] + D}{C_c \gamma_c \gamma_w D_{op}} (C_{stu} + C_{miu}) + \left[\left(\frac{\sqrt{V_s}}{24 D_{op} q_u''} \right) r + a'' \right] \right. \\ \left. (C_n'' + C_n'') + \frac{.26 Q_c (1 - C_c) 10^{-3}}{C_c D_{op}} C_{ciu} \right\} (1 + \theta'') I_N \quad (41)$$

where θ'' = a coefficient having a value approximately 0.35

Cost of Slurry Pipeline - Combining equations 18, 25, 29, and 41 will yield the capital cost of slurry pipeline. The sum of all elements need to be increased using an appropriate miscellaneous coefficient:

$$C_{cap} = [C_{SI} + C_c + C_{pump} + C_{de}] (1 + \zeta'') \quad (42)$$

where ζ'' = a coefficient having value of [1]

B - Operation Cost - Operation cost consist of costs associated with slurrification plant, water, energy, corrosion prevention chemicals, dewatering plant, labor, repair and supply, insurance, administration, and taxes. In the formulation that follows we have included the labor cost of all components including slurrification and dewatering plants within the labor category. On the other hand, energy category only includes the energy required for pumps. Other energy requirements such as the need of slurrification and dewatering plants are included in their specific components costs.

1 - Slurrification plant - The annual cost of operating the slurrification plant, excluding labor, water, and chemicals; can be written as:

$$O_{sl} = (O_{cage} + O_{rod} + O_{mix}) (1 + \sigma') \quad (43)$$

where O_{sl} = the cost of operating the plant in \$/Y, O_{cage} = the cost of operating the cage paktors in \$/Y, O_{rod} = the cost of operating the rod mills in \$/Y, O_{mix} = the cost of operating mixers in \$/Y, and σ' = a coefficient to account for miscellaneous cost in fractions.

However, using formulation of equation 4, we can write:

$$O_{cage} = (N + a) O_n \left(\frac{q_u}{q_n} \right)^\omega I_{cs} \quad (44)$$

$$O_{rod} = (N' + b) O_n' \left(\frac{q_u}{q_n} \right)^{\omega'} I_{cs} \quad (45)$$

$$\text{Also: } O_{\text{mix}} = \sqrt{V} O_m I_{\text{cs}} = \frac{W_s}{\gamma_s} O_m I_{\text{cs}} \quad (46)$$

where O_n = the cost of operation of one unit of cage-paktor with the capacity q_n T/h [300] in \$/Y [35000], O'_n = the cost of operating one unit of rod-mill with the capacity q_n T/h [300] in \$/Y [33000], O_m = the cost of operating the storage tanks and mixers in dollars per year per ton of slurry treated [.00013] ω = scale-up coefficient, (between 0 and 1), ω' = scale-up coefficient (between 0 and 1), and I_{cs} = ICC Service Consumer Price Index ratio (1977) [1.0].

When units selected for the design are of the same capacity as the units for which prices are known $q_n = q_u$ and:

$$O_{\text{cage}} = (N + a) O_n I_{\text{cs}} \quad (47)$$

$$O_{\text{rod}} = (N' + b) O'_n I_{\text{cs}} \quad (48)$$

The equation for annual cost of operation of slurrification plant can be found by combining equations 43, 46, 47 and 48 to yield:

$$O_{\text{sl}} = \left[\left(\frac{Q}{24 D_{\text{op}} q_n} + a \right) O_n + \left(\frac{Q}{24 D_{\text{op}} q_n} + b \right) O'_n + O_{\text{mix}} \right] I_{\text{cs}} \quad (49)$$

Bernstrom in 1977 presented a breakdown of operating cost for a cage-paktor and a rod-mill. ⁽⁴⁾ This is shown in Table 4.

Table 4 - Breakdown of Operating Costs of one Cage-paktor and one Rod-Mill in Cents per Ton, 1977

	<u>74" Cage-Paktor</u> (300 T/h)	<u>13' X 18' Rod-Mill</u> (300 T/h)
Power	9.86	9.28
Labor (Operating)	0.81	0.81
Liner Replacement	3.24	2.28
Grinding Rod Consumption	-	0.89
Maintenance & Supply	0.33	0.49
Repair Costs	<u>0.62</u>	<u>0.75</u>
Total	14.86	13.69
minus labor cost	<u>0.81</u>	<u>0.81</u>
Total in cents per ton	14.04	12.88

Using this information one can write for the annual cost, of operating a 300 T/h unit in dollars as:

$$O_n = .1404 \times 300 \times 24 \times D_{op} = 1011 D_{op} \approx 350,000 \quad (50)$$

$$O'_n = .1288 \times 300 \times 24 \times D_{op} = 927 D_{op} \approx 330,000 \quad (51)$$

Bernstrom data also can be used for estimating O_m . He gives the cost of operating the mixing facilities to be .0075 dollars per ton of slurry.

2 - Energy, Water, Chemical and Labor

$$O_{en} = HP \times .74 \times E_c \times 24 \times D_{op} I_e \quad (52)$$

$$O_w = \frac{[(1 - C_c)W_s - C_c W_s W]}{7.48 \times 43560} \times C_w I_{cs} \quad (53)$$

$$O_{ch} = V_s \times W_{ch} \times C_{ch} \times I_{cs} \quad (54)$$

$$O_L = N_L \times S_L \times I_{cs} \quad (55)$$

where O_{en} = annual energy cost in \$/Y, HP = the required horsepower (see equation - 28), E_c = the cost of one KWH electricity in \$/KWH, [.02], W = the coal moisture as it enters the slurrification plant in fraction [.08], C_w = the cost of one acre foot of water in \$/af [160], W_{ch} = the concentration of chemical for corrosion protection in lbs/ft³ [.001], C_{ch} = the cost of chemical in \$/lb [1600], O_L = annual average labor cost in \$/Y, N_L = the number of laborers (Mesa pipeline employees 84), and S_L = the salary of an average laborer in \$/Y [12000].

3 - Repair & Supply, Administration, Insurance, Tax, Misc.

These costs have been developed elsewhere⁽⁸⁾ and are:

$$O_{RS} = 6 \times 10^{-6} D L_p (1.00 + 9W_f) I_i + 15 H P I_e \quad (56)$$

$$\text{and } O_{in} = 0.32Q I_{CI} \quad (57)$$

$$O_{ad} = 0.7 Q I_{cs} \quad (58)$$

$$O_{tax} = \frac{r_t}{100} (C_{sl} + C_c + C_{pump} + C_{de}) \quad (59)$$

where $L_p = L_c + L_r$ = the distance between terminal of origin to terminal of destination in feet, W_f = the fraction of right-of-way in wet land (vs. dry land), [0.03], I_e = the ICC Pipeline Cost Index Ratio (1977) [1]. HP = required horse power, and I_i = the ICC Pipeline Construction Index ratio (1977) [1].

I_{cs} = the Service Consumer Price Index ratio (1977) [1], I_{CI} = the Insurance and Finance Consumer Price Index ratio (1977) [1] and r_t = the tax ratio on assessed value of the system in percent [].

4 - Dewatering plant - Since no breakdown of operating cost of individual equipment within a dewatering plant could be found in literature, the data given by Halvorsen⁽⁷⁾ was used to formulate this item. Table 5 presents the annual operating cost for a dewatering plant of 970 tons per hour of a 8 per cent moist coal.

Table 5. Operating Costs of a Centrifuge Plant in Dollar per Ton of Coal (7)

Operating Labor	0.006
Extra fuel	0.340
Power	0.189
Maintenance	
pumps	.012
centrifuges	0.170
flocculators	0.800
etc. 5%	0.120
	<u>0.898</u> 0.898
	1.433
minus labor	<u>006</u>
	$O_d = 1.427$

Thus, we may write:

$$O_{\text{dew}} = O_d Q I_o \quad (60)$$

where O_d = the cost of dewatering, in dollars per ton of coal.

Operating Cost of Slurry Pipeline - Annual operating cost of slurry pipeline, O_p , can be written as:

$$O_p = (O_{s1} + O_{en} + O_w + O_{ch} + O_L + O_{RS} + O_{in} + O_{ad} + O_{dew} + O_{\text{tax}}) (1 + \sigma) \quad (61)$$

where σ = the coefficient accounting for miscellaneous costs [1].

To calculate O_p we need to use equations 49, 52, 53, 54, 55, 53, 52, 50, 51, and 60.

Total Transportation Cost - Using Equations developed so far, allows us to calculate the annualized cost per ton-mile of transporting coal via a slurry pipeline system. This can be achieved by using Equation (2):

$$C_t^a = \frac{[F_1(C_c + 0.8C_{s1} + 0.8C_{de}) + F_2(0.2C_{s1} + C_{\text{pump}} + 0.2C_{de})] (1+r) + O_p}{QL_p/5280} \quad (62)$$

where F_1 and F_2 = capital recovery factors and can be estimated by Equations:

$$F_1 = \frac{r}{1 - (1+r)^{-n_1}}, \quad F_2 = \frac{r}{1 - (1+r)^{-n_2}} \quad (63)$$

and r is the interest rate in fraction, n_1 and n_2 are the expected lifespans of various components (20 percent of slurrification and dewatering plants assumed to have shorter life span). Using Equation (3), on the other hand, will yield the project's present value:

$$C_t^p = \frac{(1+2r) [(C_c + 0.8C_{s1} + 0.8C_{de} + C_{M1}) + \frac{n_1}{n_2} (C_{\text{pump}} + 0.2C_{s1} + 0.2C_{de} + C_{M2})] + (L_p/5280) \sum_{T=0}^{n_1} Q(1+e)^T + \sum_{T=0}^{n_1} O_p \left(\frac{1+r}{1+d}\right)^T}{(L_p/5280) \sum_{T=0}^{n_1} Q(1+e)^T} \quad (64)$$

where C_{M1} and C_{M2} are miscellaneous costs and can be estimated by finding the products of ζ times approximate capital costs.

C - Comparison

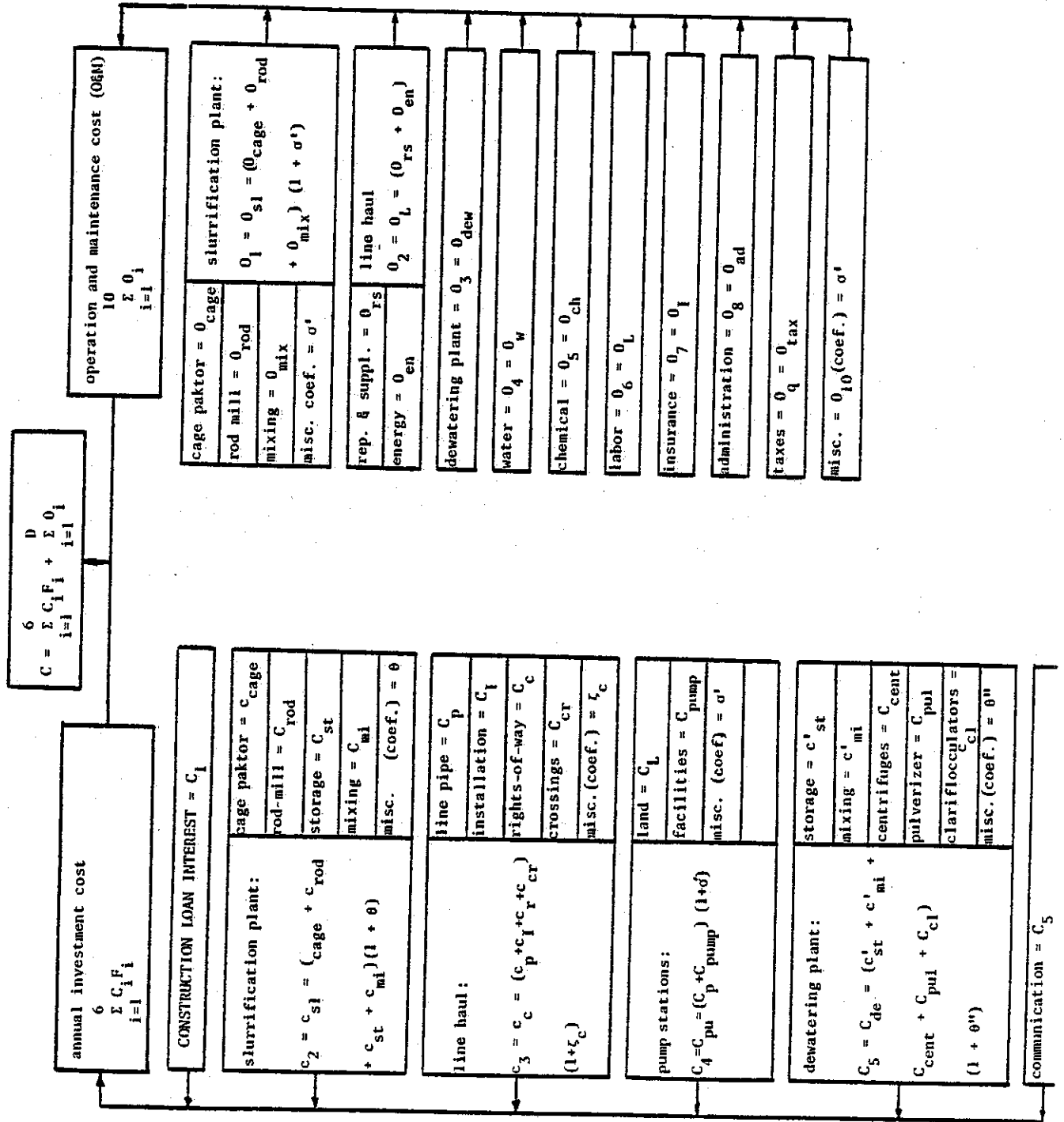
There are not very many independent cost estimates for coal slurry pipeline. The most widely accepted one has been developed by General Research Corporation under contract with the Office of Technology Assessment (OTA) of the U.S. Congress⁽⁶⁾. Since the slurry advisory panel of OTA was composed of both advocates of slurry pipeline and its agnostics the information bears at least the tacit agreement of experts. Unfortunately, the General Research Corporation's finding has not been presented in a form that it would be possible to change the conditions under which the study has been made and still be able to predict the cost. The present study, on the other hand, is formulated in such a manner that it is possible to change any parameter of the system and observe its impact on the ton-mile cost.

It is not possible to compare the results of the present study with the General Research Corporation's findings item by item because of different breakdown of the cost items. However, in the capital cost category, the total cost of installed pipeline, dewatering plant and slurrification plant can be compared. Fig. 5 compares these costs. Considering the number of variables involved, the closeness of findings is interesting.

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Fig. 1-Slurry Pipeline Annual Cost Model



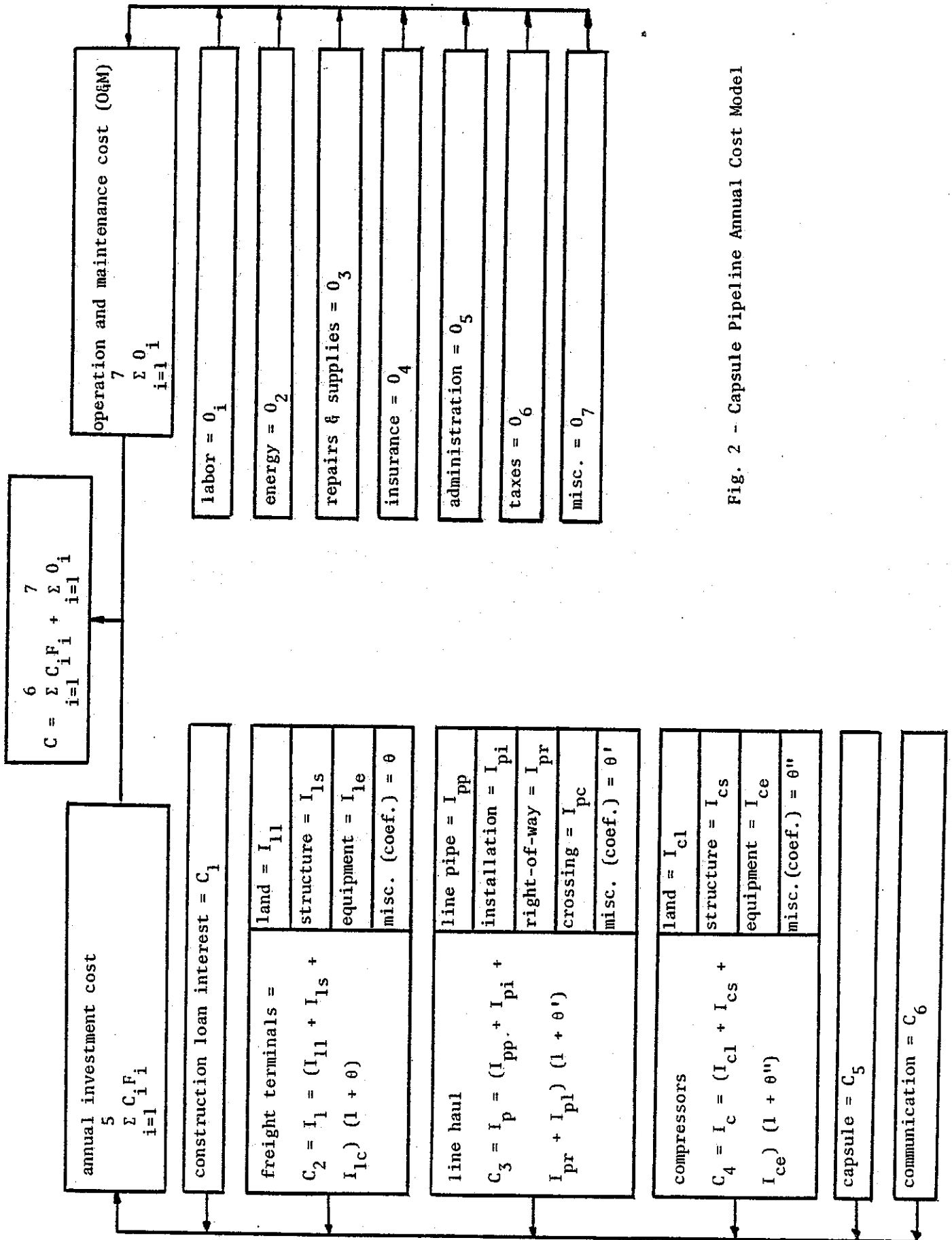
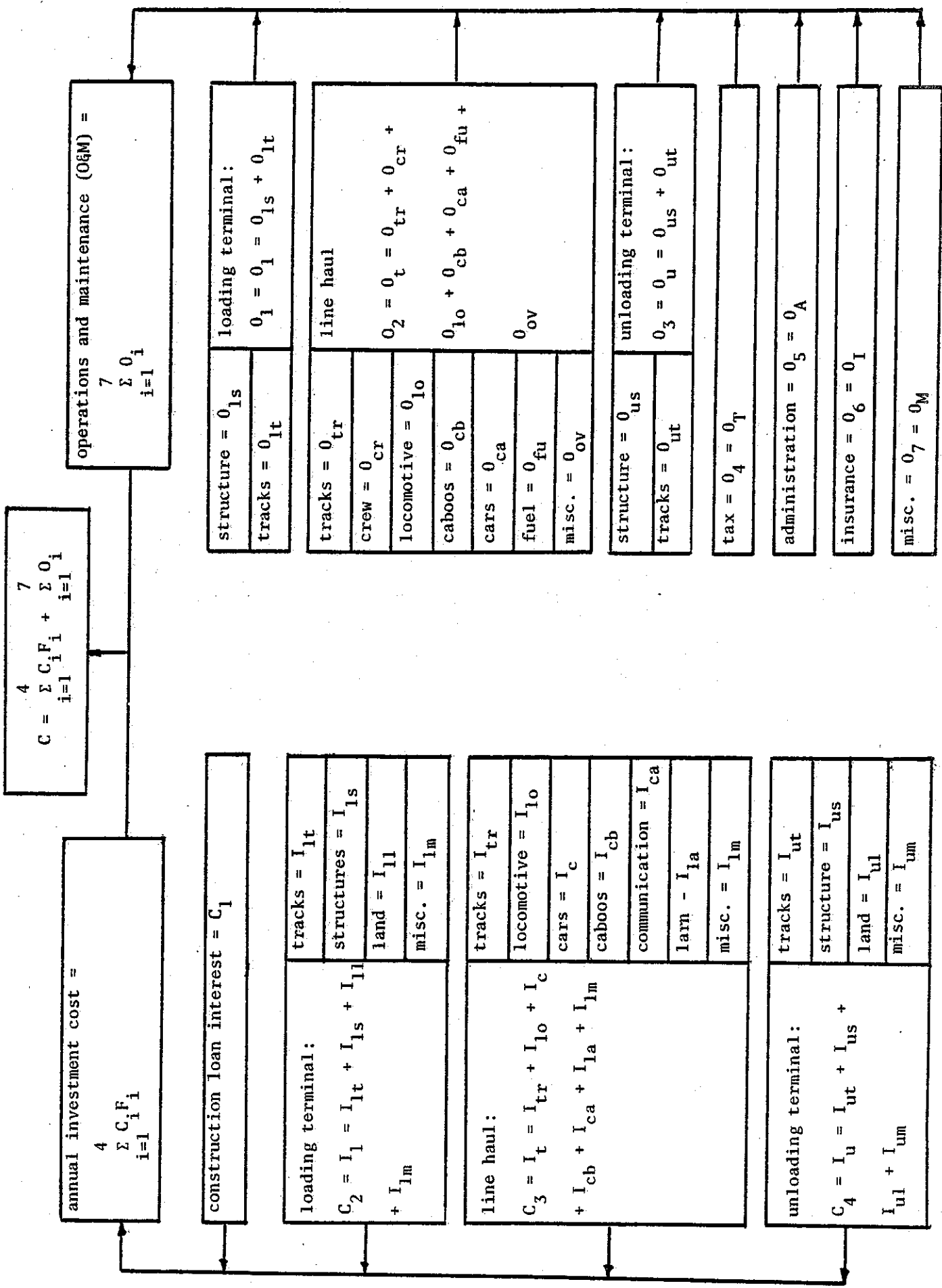


Fig. 2 - Capsule Pipeline Annual Cost Model

Fig. 3-Rail Annual Cost Model



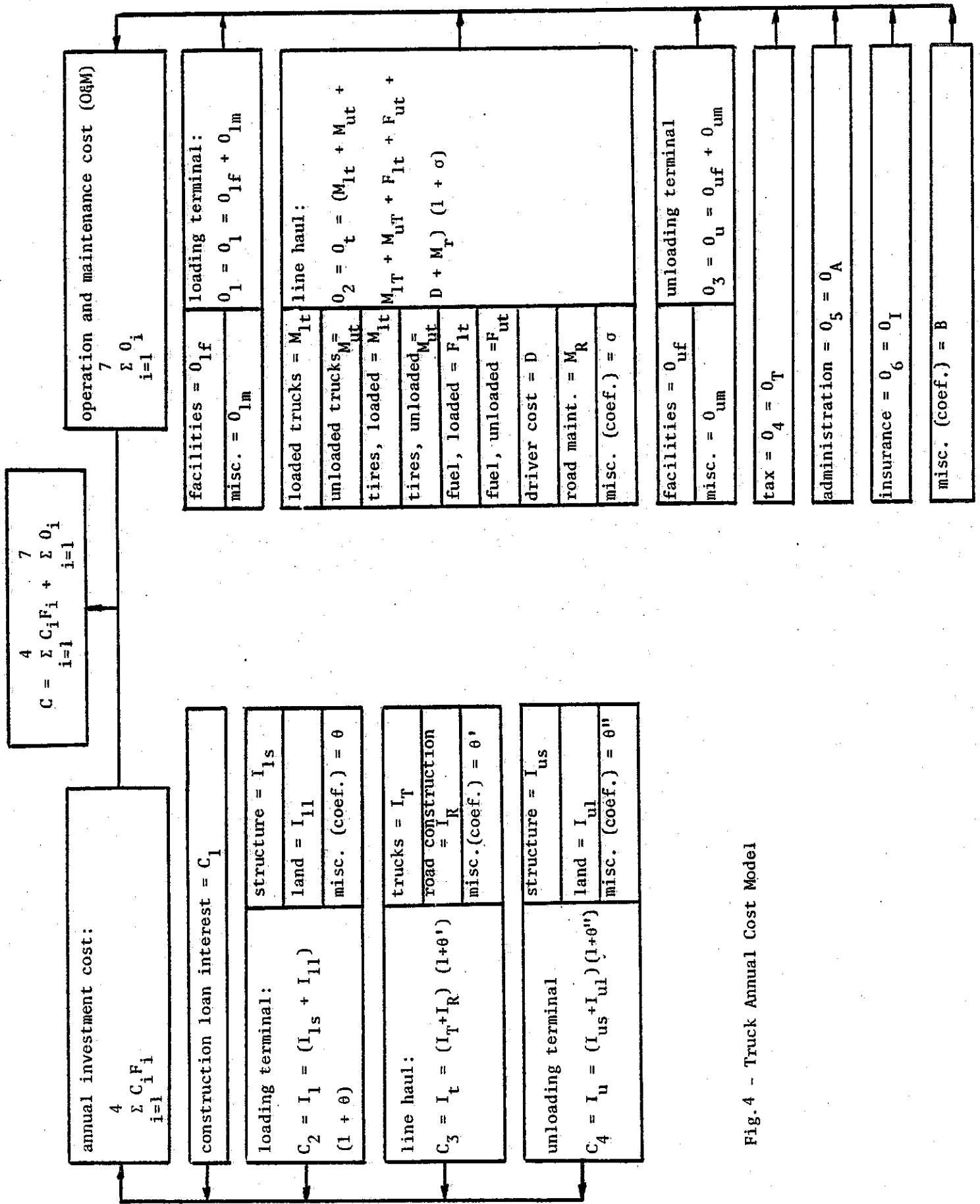


Fig. 4 - Truck Annual Cost Model

FIG. 5 COMPARISON OF CAPITAL COST PRODUCTION

