BELTCON 1

BELT CONVEYORS - DESIGN, OPERATION AND OPTIMIZATION

PAPER A1

ECONOMIC ANALYSIS IN THE OPTIMIZATION OF BELT CONVEYOR SYSTEMS

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1. SUMMARY

This paper is concerned with the development of an economic cost model to aid the decision-making process in belt conveyor design. The model involves the establishment of cost or objective functions which integrate the performance characteristics with the various cost factors involved. The cost factors include energy costs and annual equivalent cost of the conveyor components. With respect to the latter, consideration is given to such factors as equipment or component life, salvage value, taxation rates and rates of return. The effects of inflation and variations in the annual differential escalation in the energy component are included in the model. The application of the model to the design of single and multi-belt conveyor systems is described by reference to design examples.

2. INTRODUCTION

The handling of materials in bulk form is of major concern to a vast number and variety of industries throughout the world. Such industries rely heavily on the need to transport bulk solids over widely varying distances, the costs associated with these operations being very substantial. It is, therefore, most important that both high overall efficiency in terms of energy requirements, together with optimum least cost performance over the life of the installations, is obtained. For this reason, it is necessary, at the design and planning stage, to undertake detailed appraisals of various alternative handling schemes that may be employed for particular installations.

When comparisons are made between continuous modes of transport such as slurry pipelines, belt conveyors, screw conveyors and pneumatic systems and discontinuous modes such as ship or barge, road and rail, the variations in costs may differ by several orders of magnitude. Even when one mode of conveying, such as belt conveying, is examined for a particular installation, within the range of possible combinations of conveyor size, speed and plant layout, there can be considerable variations in the overall costs. For these reasons it is important that the conditions for optimum performance of particular types of conveyors and handling equipment be established.

Of the various modes of conveying of bulk solids, belt conveyors are of considerable importance in view of their widespread use and proven reliability. Although their use is mainly confined to shorter distances, they also offer advantages for long distance transportation. While their application to long distance transportation is increasing, their potential in this respect has yet to be fully realised. Following the work of Jonkers [1], when comparisons are made on an energy loss per unit distance basis, belt conveyors rank second lowest of the continuous modes, with slurry or hydraulic transport being the lowest. However, in the case of slurry pipelines, since the energy losses are a function of the transportation velocity, there is a need to specify a maximum economical velocity. Again, on an energy loss per unit basis, belt conveyors rank approximately equal to rail transport.

As demonstrated by Roberts et al [2-6], energy costs cannot be considered in isolation and design and performance evaluations of conveyor systems are only meaningful when complete economic studies, based on the total life of the plant, are made. In the work of Roberts et al an optimum design methodology has been developed in which cost functions are derived which take into account

It is convenient, in the first instance, to consider the optimum design of belt conveyors in terms of the procedures applicable to the general class of continuous conveyors for bulk solids handling. The problem is formulated in generalised form taking into account the various steps necessary in the design process.

3.2 Performance Characteristics

The design of a conveyor or system of conveyors depends on a knowledge of the relevant performance characteristics. Of particular importance are the relationships for throughput and power. While the design and operating features of the various types of mechanical conveyors differ widely, the basic performance characteristics, in functional form, are quite similar. For a given bulk material, the general relationships for throughput and power are:

Throughput (kg/s or t/h)

$$Q_m = f_2(x_1, x_2, \ldots, x_n, \rho_m, s, \alpha) \qquad (1)$$

Power (kW)

$$P_M = f_1(x_1, x_2, \ldots, x_n, \rho_m, L, s, \alpha) \qquad (2)$$

In the above relationships $(x_1, x_2, \ldots x_n)$ are geometrical design variables applicable to the particular conveyor, ρ_m is the bulk density of the material being conveyed, L is the overall conveyor length, s is the conveyor speed and α is the angle of elevation. It is to be noted that for most continuous type conveyors, the throughout Q_m is independent of the conveyor length, as indicated by equation (1).

The geometrical variables are those that express the carrying capacity (and power) in terms of a unit conveyor length. For example, in the case of a belt conveyor, they include the belt width, number of plies, idler configuration (number of rollers and troughing angles) and idler spacing. For a screw conveyor they include the screw diameter, pitch, core diameter, choke length and casing clearance. For a bucket elevator they include the belt width, bucket capacity and bucket spacing.

In the case of multiple length conveyors the overall length will be given by the energy costs and annual equivalent cost computed on a life cycle basis. The latter requires consideration of such factors as equipment or component life, salvage value, taxation rates and rates of return. The effects of inflation and variations in the annual differential escalation in the energy and component costs are included in the model. Optimum, minimum cost solutions to the conveyor design problem are sought taking into account constraints imposed by design, manufacturing and operational limitations. The optimum solutions may be implemented directly or used as a 'yardstick' against which the actual conveyor performance can be measured.

The purpose of this paper is to describe the application of the aforementioned economic analysis to the optimum design of belt conveyors. Both single and multiple conveyor systems are discussed.

3. THE GENERALISED CONVEYOR DESIGN PROBLEM

3.1 Introductory Remarks

The problem of conveying a bulk solid by belt conveyor from one point to another is depicted, schematically, in Figure 1. Over short distances a single conveyor will be used as in Figure 1(a) whereas for long distance transportation, a multiple conveyor system as in Figure 1(b) will need to be considered. In the latter case it becomes necessary to determine the most desirable number of individual conveyors and their corresponding lengths.

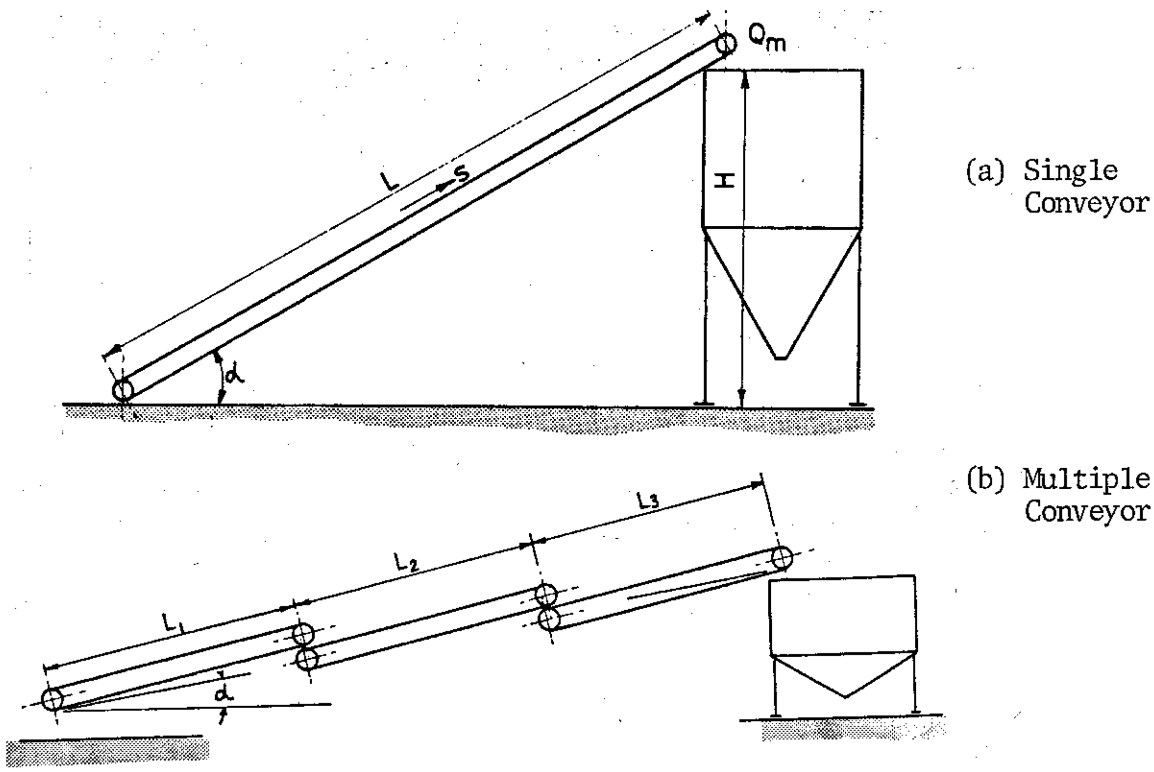


Figure 1 Schematic Arrangement of Belt Conveyors for Bulk Solids Handling

$$L = \sum_{i=1}^{N} \ell_i \qquad (3)$$

where ℓ_i = length of i th conveyor

and N = number of conveyors involved.

For conveyors used to elevate bulk materials, the overall efficiency is of importance in the performance assessment. The overall efficiency relates the theoretical power to elevate a bulk material in the absence of friction to the actual power. That is

$$\eta_0 = \frac{Q_m \, g \, L \sin \alpha}{3600 \, P_M} \qquad (4)$$

where Q_m = t/h

In addition to the performance equations (1), (2) and (4), it is necessary to establish a relationship which takes into account the over-riding geometrical requirements governing the conveying distance and height of lift. That is, a relationship is needed which expresses the effective height of lift H(m) as a function of conveyor length and angle of elevation α. Knowing the required height of lift, an additional height allowance must be made to permit the gravity flow of the bulk material from the outlet of the conveyor through some discharge device such as a transfer chute.

In general terms

$$H = f_3(L, \alpha) \qquad (5)$$

By way of example, an appropriate function for the conveyor of Figure 1(a) is

$$H = \frac{L \sin \alpha}{1 + C_H \sin \alpha} \quad \text{for } 0 < \alpha < \frac{\pi}{2} \qquad (6)$$

where C_H = coefficient based on conveyor geometry

3.3 Design Constraints

In addition to the need to satisfy the performance and geometrical requirements, the design analysis must take into account certain additional constraints. These fall into two main groups:

3.3.1 Functional Constraints

These govern the need for the conveyor components to be designed for strength, safety and reliability. The actual magnitude of the conveyor geometrical variables may often be dictated by the strength and life characteristics of the component materials. For example, the number of plies p in a conveyor belt, as well as depending on the belt width B and maximum belt tension F_{max}, also depends on the safe working stress of the belt material σ_b

That is

$$p = f_4(\sigma_b, B, F_{max}) \qquad (7)$$

3.3.2 Constraints on System Variables

Practical considerations usually create the need to constrain the conveyor variables so that they lie within fixed limits. For instance the upper limit on belt conveyor speed is dictated by the need to ensure efficient tracking and to minimise component wear. Normally belt speeds are limited to a maximum value of 6 m/s but in view of the current improved technology, belt speeds greater than this are being used.* Belt widths are limited by manufacturing capabilities. Hence in general terms we can write

$$\left.\begin{array}{l} x_{1\ell} \le x_1 \le x_{1u} \\ - - - - - - - - \\ x_{n\ell} \le x_n \le x_{nu} \\ s_\ell \le s \le s_u \\ \alpha_\ell \le \alpha \le \alpha_u \end{array}\right\} \qquad (8)$$

3.4 Design Solution

The design of a conveyor to satisfy the specified performance requirements will involve the consideration of a number of alternative solutions. In theory, computations based on the relationships of (1) and (2) together with the constraints of the type given by (5), (7) and (8) will yield a large number (in fact an infinite number) of solutions in the 'solution space', all of which meet the required performance conditions. A decision needs to be made as to which of the possible solutions is the most appropriate. For this reason additional criteria

* The Rheinische Braunkolinwerke in West Germany operate 2.5 m wide belt conveyors running at 7.5 m/s.

need to be laid down to aid the decision-making process. Such criteria, inevitably, must take account of the need for efficient and economic operation.

By establishing appropriate cost or objective functions it is possible to obtain optimal solutions to conveyor design problems. Such objective functions need to be derived on the basis of detailed economic considerations, as outlined in the next sections of this paper. Objective functions obtained in this way will have the functional form

$$I = I(x_1, x_2, \ldots , x_n, \rho_m, s, L, \alpha) \qquad (9)$$

The objective is to determine the system variables (x_1, x_2, ... x_n, s, L, α) that minimise I subject to the required performance condition or throughput expressed by (2). The solution must take account of the various system constraints such as those given by equations (3), (5), (7) and (8).

In general terms the design analysis is transformed into a constrained, non-linear optimization problem. While several known computing algorithms for this class of problem exist [7], two have been found to be effective for the solutions of conveyor optimization problems. These are the constrained Fletcher-Powell (Conmin) algorithm which has been adapted by Khaw [8] for the solution of screw conveyor design problems and the Box (complex) algorithm which was also examined by Khaw and more recently by Lim [10] for belt conveyor problems. A modification of the complex algorithm based on reference [9] has also been examined by Lim for the case of discrete valued variables optimization problems which are more representative of actual belt conveyor design problems.

While optimum solutions may be found in this way, it is important to note that the optimization algorithm is not going to be the final answer in all cases. At least perturbations of the solution about the optimum will show how sensitive the operating costs are to variations in the performance variables. If the independent variables are few in number and the general range of these variables for a feasible solution is known, then it is often easier to determine the optimum solution by repeated computation of the cost function I for the selected range of variables. This procedure may be preferable where, as in many cases, the variables need to be discrete values or integers such as belt width and the number of plies comprising the belt.

4. ECONOMIC CONSIDERATIONS

The costs incurred in a conveyor system may be divided into two categories

(i) Capital costs

(ii) Operating costs.

Any form of economic evaluation must express both types of cost in some common measure. By specifying a rate of return required on the capital funds employed, costs may be expressed as present equivalent costs or as annual equivalent costs over the life of the system.

4.1 Annual Equivalent of Capital Cost

For the belt conveyor the capital cost items include

- Drive system, motor, speed reducers
- Belt
- Idlers
- Structure
- Transfer stations (in multi-conveyor systems)

The costs need to be determined on a life cycle basis. Depending on the accuracy required, the analysis may be on the basis of cash flows

- Before tax
- After tax without considering inflation
- After tax considering inflation

Only the last of these will be described as the other two are readily derived from it.

If all costs are expressed as the inflated dollar expenses expected to be incurred at the time they occur, then for capital items not needing replacement during the life of the system, n, the present equivalent of these capital costs, PEC, is given by [14]

$$PEC = \frac{A - V\left(\frac{P}{F}\right)_{n}^{i_f} - t(PED)}{1 - t} \qquad (10)$$

where A = First cost of the item

V = Salvage value

t = Tax rate

PED = Present equivalent of depreciation

i_f = Inflation modified rate of return

$$\left(\frac{p}{f}\right)_n^{i_f} = \frac{1}{(1+i_f)^n} = \text{Present equivalent factor.}$$

For a company maintaining a constant proportion of debt capital, r_d, then i_f is given by

$$i_f = (1-t)r_d\, i_d + (1-r_d)[(1+r)(1+i_e) - 1] \qquad (11)$$

where i_d = interest rate on debt

i_e = after tax return required on equity funds with zero inflation rate.

The annual equivalent cost, in year zero dollars, may be obtained by multiplying the present equivalent by the capital recovery factor,

$$\left(\frac{a}{p}\right)_n^{i_f^o} = \frac{i_f^o\,(1+i_f^o)^n}{(1+i_f^o)^n - 1}$$

that is

$$AEC = PEC \left(\frac{a}{p}\right)_n^{i_f^o} \qquad (12)$$

The factor i_f^o which expresses the time value of money when all cash flows are expressed in constant year zero dollars rather than inflated dollars is given by

$$i_f^o = \frac{(1-t)r_d\, i_d - r\, r_d}{(1+r)} + (1-r_d)i_e \qquad (13)$$

For any item which may require replacement during the life of the conveyor system, the values of A, V and PED in equation (10) are modified to include the present equivalents of the original and all replacement items required.

By expressing salvage values and depreciations as a fraction of first cost A, the annual equivalent cost of any item can be expressed as a fraction of its first cost and hence as a function of the operating and geometrical variables of the system. By expressing all costs in this form and summing, the total annual equivalent cost is obtained.

4.3 Operating Costs

For a given conveyor or handling system the operating costs include

- Energy
- Repairs and maintenance
- Labour

4.3.1 Energy Costs

The annual energy cost may be calculated from the annual energy consumption. That is

$$I_1 = k_1 \, e_c \, p \qquad (14)$$

where e_c = annual hours of operation times the unit cost of energy

k_1 = annual equivalent energy cost coefficient taking into account inflation and annual escalation rate of energy costs

It is worth noting that a considerable amount of energy is expended in overcoming frictional resistance. This will vary with the speed and design features of the particular conveyor and the bulk density of the material. A typical belt conveyor could require as much as 30% of the total power requirement to move the empty belt.

In some studies it may be desirable to allow for the possibility of energy costs rising more rapidly than the general inflation rate. If

r = general inflation rate

r_e = annual escalation rate of energy costs

e_{co} = energy cost at time zero

e_{cz} = energy cost in year z

then

$$e_{cz} = e_{co} \, (1 + r_e)^z \qquad (15)$$

The present equivalent of energy costs over the life of the system n is given by

$$PEC = \sum_{z=1}^{n} e_{co} \left[\frac{1 + r_e}{1 + i_f}\right]^z \qquad (16)$$

The annual equivalent in year zero dollars is obtained by multiplying by the capital recovery factor $(\frac{a}{p})_n^{i_f^o} = \frac{i_f^o(1 + i_f^o)^n}{(1 + i_f^o)^n - 1}$

that is

$$AEC \text{ (energy)} = e_{co} (\frac{a}{p})_n^{i_f^o} \sum_{z=1}^{n} \left[\frac{1 + r_e}{1 + i_f}\right]^z \qquad (17)$$

Thus k_1 in equation (14) becomes

$$k_1 = (\frac{a}{p})_n^{i_f^o} \sum_{z=1}^{n} \left[\frac{1 + r_e}{1 + i_f}\right]^z \qquad (18)$$

4.3.2 Repairs and Maintenance

Although this is an important item, little is known of the relation with the operating parameters such as speed and belt width. For overall estimates it is often taken as some percentage of the overall cost of capital items plus some percentage of the belt cost [12]. This given no insight into the variation with operating parameters. Intuitively on general grounds it may be expected that maintenance cost and costs associated with overall reliability would increase with the speed of the conveyor. This may be seen, for example, when the life of the idlers is considered. The life of the idler bearings decreases as both the load and rotational speed (and hence belt speed) increase. However, due to ignorance of the form of the repairs and maintenance cost functions, these costs have not been included in the model. The assumption of these costs being a fixed percentage of the overall cost is made; as a consequence the costs based on this assumption will not influence the operating parameters which justifies the exclusion of these cost items.

4.3.3 Labour

In comparing the belt conveyor with an alternative for a particular application, labour costs for operation may be quite significant. In optimizing a belt conveyor for a particular application, the labour is unlikely to change with a different choice of operating parameters. For this reason no labour costs have been included.

5. ECONOMIC ANALYSIS APPLIED TO BELT CONVEYOR DESIGN

5.1 Problem Specification

Consider the problem of designing a typical belt conveyor installation as shown in Figure 1(a) or 1(b). The conveyor is required to transport a bulk solid of density ρ_m (kg/m^3) at a rate of Q_m (kg/s) over a distance L (m) and height of lift H (m).

5.1.1 Design Assumptions

The design requires some assumptions to be made, such as

- The proposed idler configuration
- The proposed belt type
- The proposed belt and drive configuration to suit the particular application.

5.1.2 Conveyor Variables

The relevant geometrical design variables are

$x_1 = B =$ belt width

$x_2 = p =$ number of plies (Note: p must be an integer)

$x_3 = \beta =$ idler troughing angle for two roller or three roller idler configuration

$x_4 = \lambda =$ idler contact perimeter ratio for nominated idler configuration

$x_5 = a_o =$ idler spacing or carrying side (m)

$x_6 = a_u =$ idler spacing on return side (m)

$x_7 = \ell =$ length of individual conveyors in multiple conveyor system (m)

Also $v = s =$ belt velocity (m/s)

5.2 Performance Characteristics

While the general design procedures for belt conveyors are well documented, for the purpose of the present discussion the essential equations given in references [5] and [6] are summarised here.

5.2.1 Throughput Q_m

This is given by

$$Q_m = \rho_m A v \cos \alpha \qquad (19)$$

Normally the angles of inclination α are low enough for $\cos \alpha \approx 1$. Hence

$$Q_m = \rho_m A v \qquad (20)$$

where $A = U b^2$ (21)

U = Non-dimensional cross-sectional area shape factor

b = contact or 'wetted' perimeter (m)

Shape factors can be determined for different idler configurations:

- Single Idler - Flat Belt

$$U_1 = \frac{\tan \delta}{6} \qquad (22)$$

where δ = surcharge angle

- Two Idler System

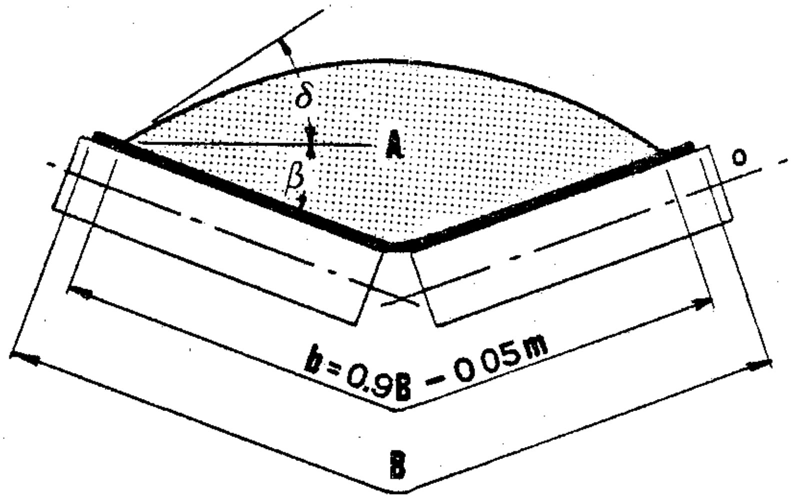


Figure 2 Two Idler System

$$U_2 = \frac{\sin 2\beta}{8} + \frac{\tan \delta}{12} (\cos 2\beta + 1) \qquad (23)$$

For maximum U_2

$$\tan 2\beta^* = \frac{3}{2 \tan \delta} \qquad (24)$$

- Three Idler System

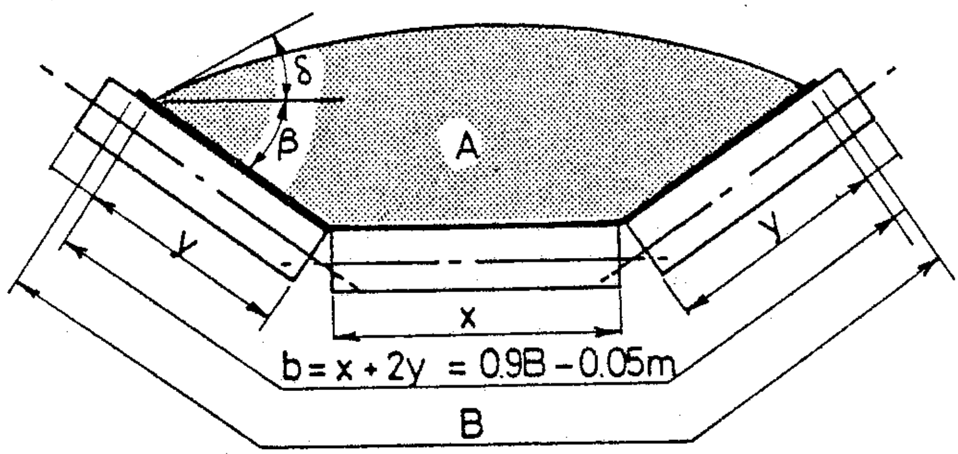


Figure 3 Three Idler System

$$U_3 = \frac{1}{1+2\lambda)^2}\{\lambda \sin\beta + \frac{\lambda^2}{2}\sin 2\beta + \frac{\tan\delta}{6}[1+4\lambda\cos\beta + 2\lambda^2(1+\cos 2\beta)]\} \quad (25)$$

where $\lambda = y/x$

For given values of δ and λ, the angle β^* for maximum U_3 is given by

$$\cos\beta^* + \lambda\cos 2\beta^* - \frac{2}{3}\tan\delta\,(\sin\beta^* + \lambda\sin 2\beta) = 0 \quad (26)$$

Alternatively, for given values of δ and β, the ratio λ^* for maximum U_3 is given by

$$\lambda^* = \frac{\frac{2}{3}\tan\delta\,(1-\cos\beta) - \sin\beta}{\sin 2\beta + \frac{2}{3}\tan\delta\,(1+\cos 2\beta) - 2\sin\beta - \frac{4}{3}\tan\delta\cos\beta} \quad (27)$$

The belt width B is expressed in terms of the contact permiter b allowing for edge effects

$$B = 1.11\,b + 0.056\ (m) \quad (28)$$

5.2.2 Conveyor Power

In simplified terms the total resistance F_U of a conveyor belt is

$$F_U = C[F_{H1} + F_{H2}] + F_{st} + F_{s1} + F_{s2}\ (kN) \quad (29)$$

where F_{H1} = Empty belt frictional resistance

F_{H2} = Load frictional resistance

F_{st} = Slope resistance

F_{S1}, F_{S2} = Special resistances

C = Factor to allow for secondary resistances such as those due to accelerating the material onto the belt.

The factor C is given in reference [11]. Alternatively it may be expressed as

$$C = 0.85 + 13.31\, L^{-0.576} \quad \text{for } 10 < L < 1500 \text{ m}$$
$$C = 1.025 \quad \text{for } 1500 < L < 5000 \text{ m} \tag{30}$$

The required motor power is

$$P_M = \frac{F_U\, v}{\eta} \tag{31}$$

where η = drive efficiency

5.3 Belt Design

Based on the simplified drive analysis the wrap factor C_w for a given angle of wrap θ (radians) on the driving pulley(s) may be approximated by

$$C_w = \frac{1}{e^{\mu\theta} - 1} \tag{32}$$

where μ = Friction coefficient between the belt and pulley

The slack side tension is

$$F_2 = C_w\, F_U \tag{33}$$

and tight side tension is

$$F_1 = F_U + F_2 \tag{34}$$

The maximum belt tension will be the larger of the values of F_1 and that computed from the conveyor layout where it is necessary to limit the belt sag between the idlers.

For an assumed belt type, the allowable stress is given by σ_b (kN/m, ply). Thus for a given belt width B the required number of plies is given by

$$p = \frac{F_{max}}{B\ \sigma_b} \qquad (35)$$

where p = integer value

5.4 Economic Considerations

The cost components are expressed as an annual equivalent cost based on the life of the plant. The actual cost values are in dollars Australian but are readily convertible to other currencies. While the relative differences between the energy and component costs may vary from one country to another, the objective of this study is to present the general principles by which economic design may be achieved. Individual cost variations can be readily catered for via the use of the various coefficients incorporated in the design model.

5.4.1 Energy Costs

The annual equivalent cost of the energy is given by equation (14)

$$I_1 = k_1\ e_c\ P \qquad (14)$$

5.4.2 Capital Cost Items

For all these items it has been found possible, over restricted ranges, to express the first cost as a linear function of the operating and design variables [5,6]. The annual equivalent capital cost is obtained by multiplying the first cost by a coefficient determined on the basis of the economic analysis previously described. The annual equivalent cost relationships may be summarised as follows:

Motor

$$I_2 = k_2(c_1 + c_2\ P_M) \qquad (36)$$

Gear Reducer

$$I_3 = k_3(c_3 + c_4\ T_R) \qquad (37)$$

Conveyor Belting

$$I_4 = k_4(c_5 + c_6\ B)\ KL \qquad (38)$$

Idler Pulleys

$$I_5 = k_5(c_7 + c_8\ B)\ \frac{L}{a_o} \qquad (39)$$

for carrying side

$$I_6 = k_6(c_9 + c_{10} B) \frac{L}{a_u} \quad (40)$$

for return side

In the above equations c_1, c_2 .... c_{10} are first cost coefficients; k_2, k_3 .... k_6 are annual equivalent cost coefficients; P_M is the power; T_R is the transmitted torque; B is the belt width; a_o and a_u are spacing of idlers on carrying and return side respectively; L is the conveyor length. The factor K in equation (33) allows for the total belt length, taking into account such factors as take-up pulleys and trippers; ($K \geq 2$). It should be noted that the coefficients c_5 and c_6 for the conveyor belting are a function of the belt type and number of plies.

As shown by Heaney [13], the conveyor structure, which is a function of the belt width, is a major component of the overall cost and should be taken into consideration. The supporting structure is assumed to consist of two steel main beams, braced at intervals, with a walkway at each side. A typical cross-section is shown in Figure 4. The structure is assumed to be supported at 5 m intervals.

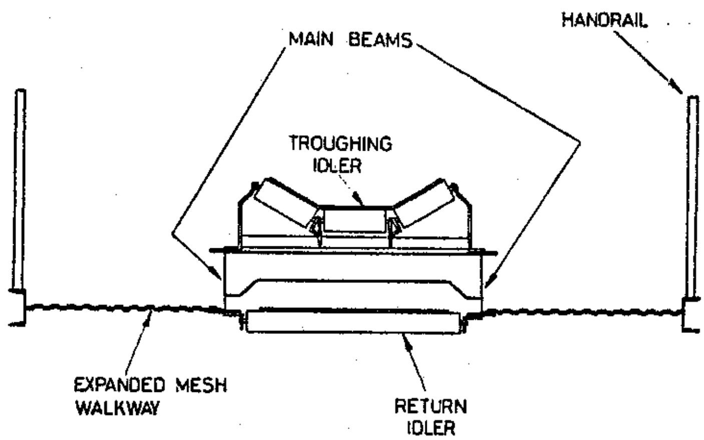


Figure 4 Conveyor Structure

Other capital cost items include the belt tensioning arrangements, discharge arrangements and drive couplings. Although the cost of these items is dependent, to some extent, on the conveyor width, capacity and operating parameters, as far as the overall cost is concerned their contribution may be assumed constant. For this reason they need not be included in the cost or objective function.

The overall cost or objective function is the summation of all the component costs, as indicated by equation (9).

5.4.3 General Comment

It should be noted that the component costs, such as, for example, those associated with the gear reducer, are not really continuous functions as assumed in the preceding equations. The costs are really stepwise functions which are dependent on the available standard size range of the components. This is illustrated in Figure 5.

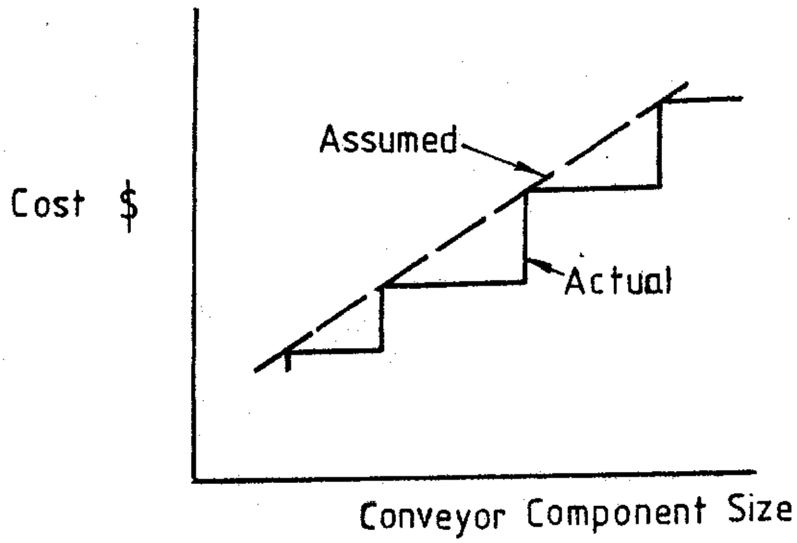


Figure 5 Cost Functions for Conveyor Components

6. BELT CONVEYOR EXAMPLE

6.1 Design of Single Conveyor

A belt conveyor, 500 m long, is required to convey a bulk material of bulk density ρ_m = 850 kg/m^3 up an incline of 1 in 10 and discharge it at a rate of Q_m = 600 t/h.

6.1.1 Principal Design Assumptions

- Idlers - 3 roll system with λ = 1 and β = 35°
- Surcharge angle δ = 20°
- Belt type - Kuralon/Nylon (Type KN 150)
  Allowable stress σ_b = 15.8 kN/m, ply
- Gear reducer - helical type
- Operation - 12 hours/day over 300 days per year

6.1.2 Design Constraints

Belt width $0.65 \leq B \leq 1.6$ (m)

Plies $2 \leq p \leq 8$

Belt speed $0.5 \leq v \leq 6$ (m/s)

6.1.3 Economic Considerations

The basic assumptions are

- General inflation rate is 10%.
- Energy costs - unit cost of energy is \$0.06 per kW/hr. - annual cost escalation rate is 15%.
- Installation - life of the conveyor and drive components is 12 years. Salvage value is zero. Cost escalation rate per year for drive and structure is 10%.
- Conveyor belting and idler pulleys - life of 7 years is assumed with zero salvage value. The belt and idlers are replaced after the seventh year and are then depreciated and written off at the end of the twelfth year. The price escalation rate per year for these components is 10%.
- After tax rate of return on equity capital is 5%.
- Taxation rate is 0.46.
- Depreciation by straight line method.

With these assumptions the annual equivalent cost coefficients are:

Energy	k_1 =	1.317
Motor	k_2 =	0.166
Gear reducer	k_3 =	0.166
Conveyor belting	k_4 =	0.260
Carrying idlers	k_5 =	0.260
Return idlers	k_6 =	0.260
Structure	k_7 =	0.166

The method of calculating the above coefficients is illustrated in the Appendix.

6.1.4 Design Solutions

To gain some appreciation for the cost variations involved by considering alternative design solutions, cost functions have been computed for a range of belt widths. The results are shown in Figure 6. Figure 6(a) shows the variation of velocity, power and number of plies as a function of belt width; the corresponding annual equivalent cost curves are presented in Figure 6(b). In Figure 6(b) the lower curve is the cost excluding the structure while the upper curve is the total cost including the structure.

In the solution of the conveyor design problem consideration needs to be given to the constraints which have been previously indicated, as well as to the need for some of the design variables to be discrete values. A possible solution in this case is

Belt width B = 0.65 m (a preferred size)

Number of plies = 4

Belt speed = 4.21 m/s

Power = 146 kW

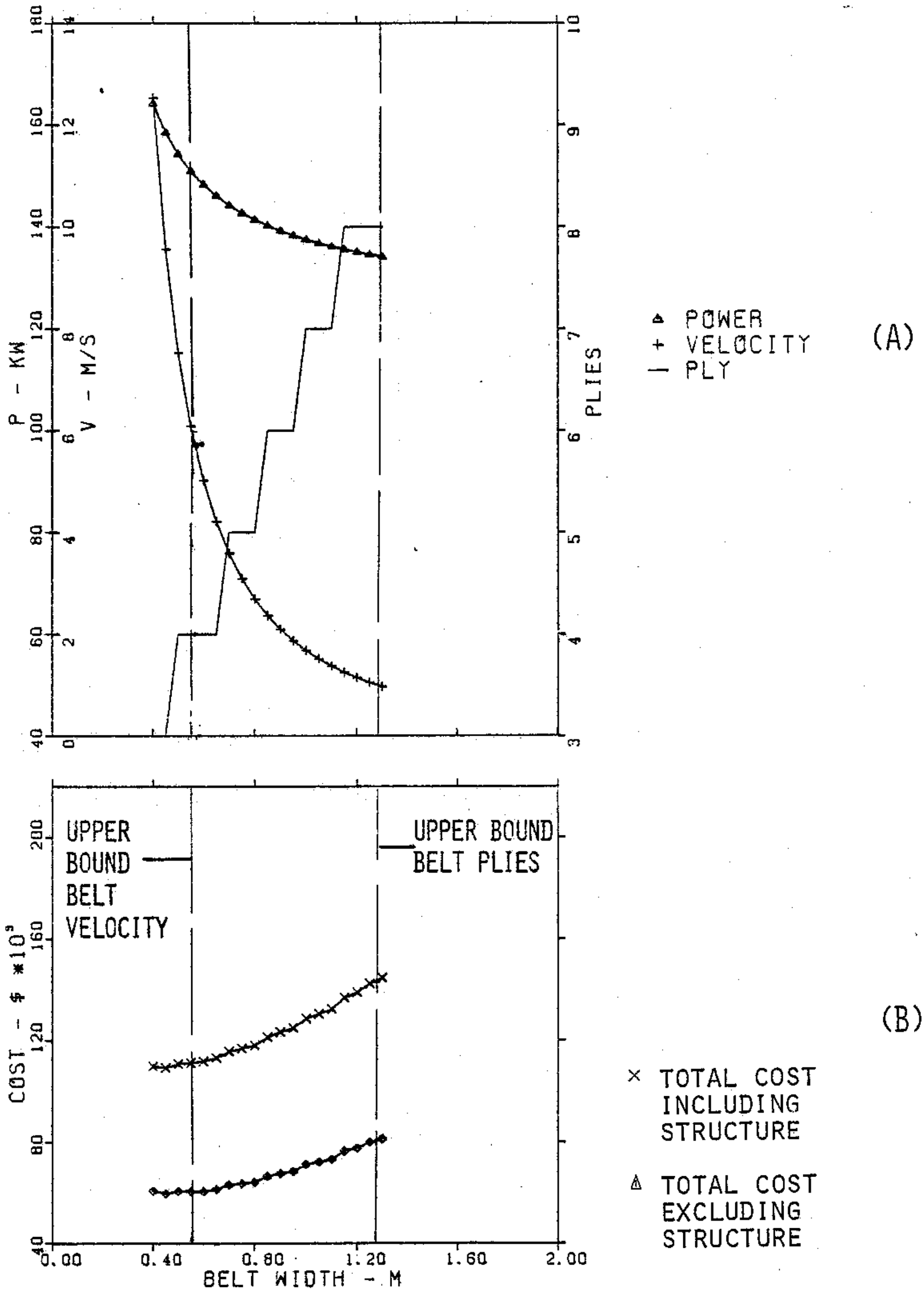
Total annual cost I_C = \$61,300, excluding structure

I_T = \$113,200, including structure

It is useful to examine the contributions of each item in the overall cost. This information is presented in Figure 7 and, as can be seen, the over-riding contribution is that due to the structure. With respect to the actual conveyor components, the substantial cost is that due to the belt. The energy cost is a major component in this case, the energy to overcome the slope resistance being a major contributing factor.

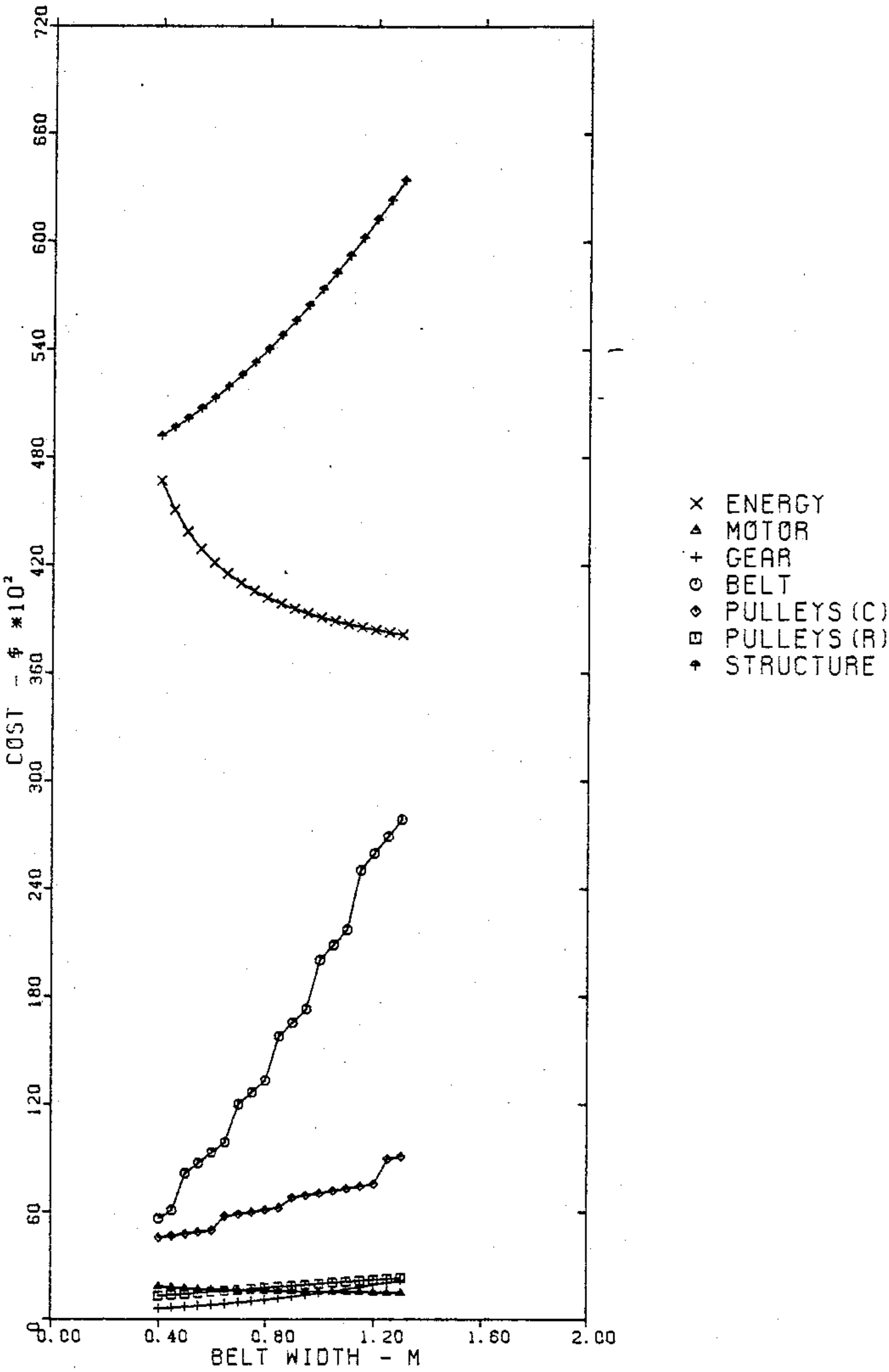
The example clearly demonstrates the advantages of using narrower, faster-running belts. For instance, doubling the belt width reduces both the required belt speed and the power requirements but results in an increase of 28% in the overall cost.

Figure 8 shows the break-up of the various components of the power as a function of belt width. For comparison purposes the belt velocity is also shown.



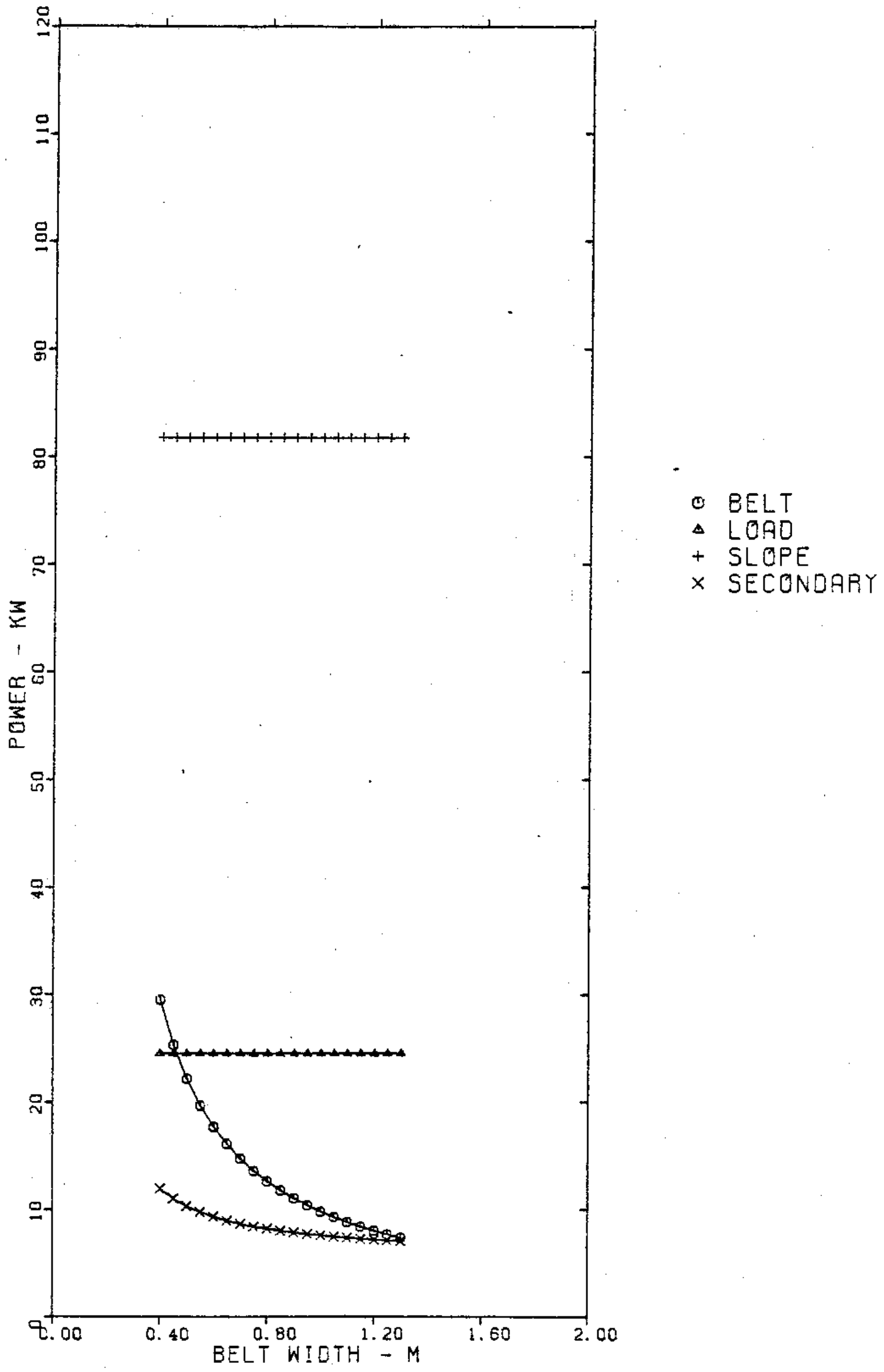
PERFORMANCE AND OVERALL COST
CHARACTERISTICS FOR BELT CONVEYOR
Q= 600 T/HR, L= 500M, H= 50 M

Figure 6



BELT CONVEYOR COMPONENT COSTS

Figure 7



CONVEYOR POWER COMPONENTS
Q= 600 T/HR, L= 500M, H= 50 M

Figure 8

6.2 Influence of Variable Inflation Rates

To illustrate the effects of variations due to cost escalation, the same problem as in 6.1 was examined for the case where the annual cost escalation rate is 20% for the energy costs and 15% for the belt, all other parameters being the same as before. In this case

$k_1 = 1.751$

and $k_4 = 0.298$ (see Appendix for computation of this coefficient)

The comparable annual costs for the conveyor alone and for the conveyor plus structure are, respectively,

$I_C = \$76,415$

$I_T = \$128,364$

6.3 Comparison between Two and Three Idler System

Consider the same problem as in 6.1 but in this case a two idler system with $\beta = 35°$ is to be used. With the same conditions applicable as in 6.1 the suggested solution is indicated in Table 1. For comparison purposes the solution for the three idler system is also included.

TABLE 1 Comparison between Two and Three Idler Systems
$Q_m = 600$ t/h, $\rho = 850$ kg/m³, L = 500 m, H = 50 m

	Two Idler System $\beta = 35°$	Three Idler System $\beta = 35°$ $\lambda = 1.0$
Belt width B (m)	0.65	.65
Number of plies	4	4
Belt speed m/s	5.70	4.21
Power kW	138	146
Annual Cost I_C	\$63,420	\$61,300
Total Annual Cost I_T	\$114,700	\$113,200

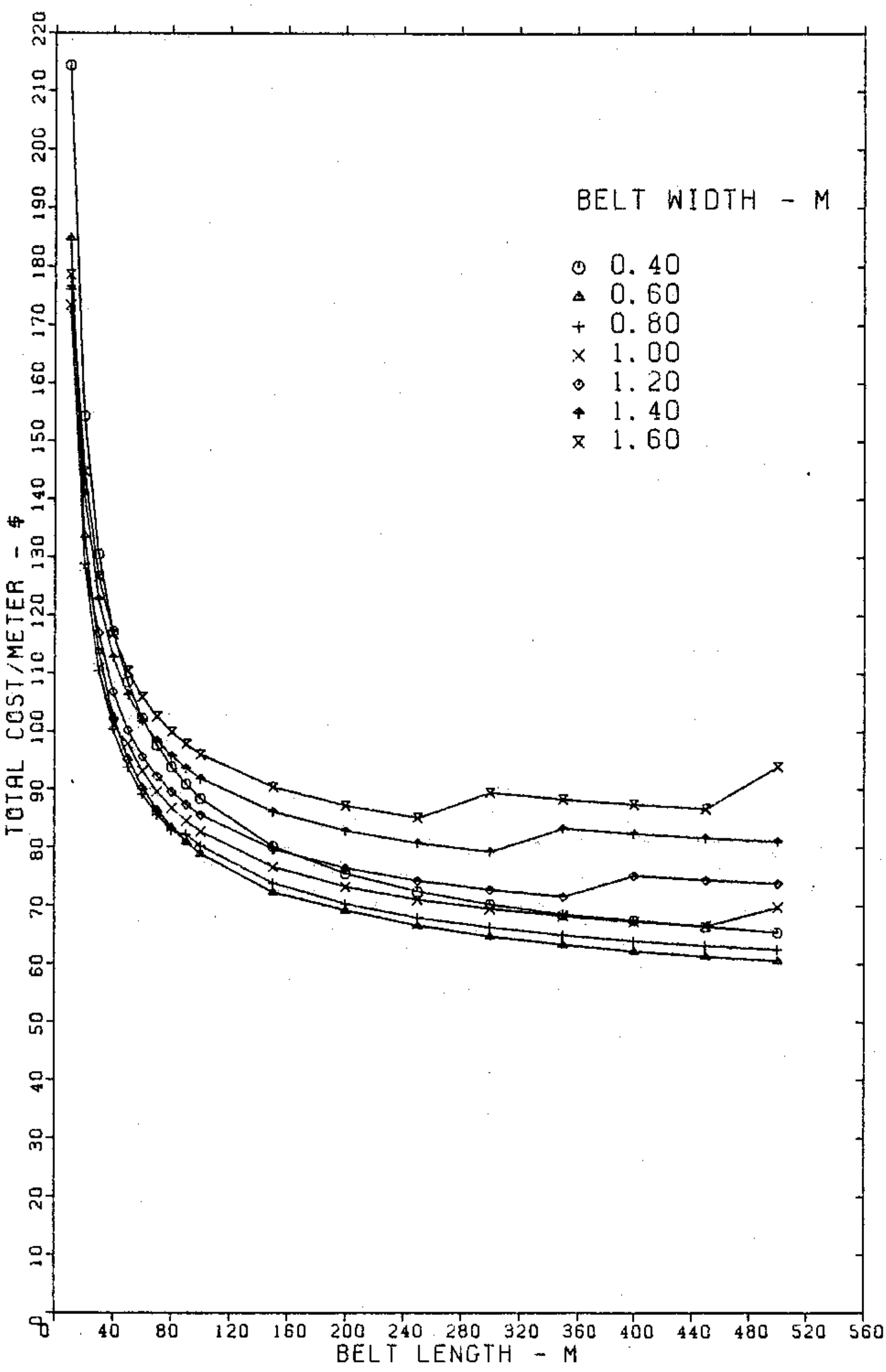
7. MULTIPLE CONVEYOR SYSTEMS

Where materials are to be conveyed by belts over long distances, multiple conveyors, as illustrated in Figure 1(b), need to be employed. The choice of the number of conveyors and the individual length of each component conveyor will often be dictated by the design constraints such as the need to limit the maximum belt tension to suit the maximum number of plies available. However, it is also evident that in view of the cost variations per unit length, it is important that economic factors are taken into account.

By way of illustration, the annual equivalent costs per unit length of conveyor have been determined for the case where the throughput is $Q_m = 600$ t/h, bulk density $\rho_m = 850$ kg/m^3 and the slopes are zero in one case and 1 in 10 in another. All other relevant parameters are the same as in the previous example of Section 6.1. Figures 9 and 10 show, for the two cases, the annual equivalent cost per metre length as a function of belt length for a range of belt widths. The range of belt lengths considered is from zero to one kilometre.

In both cases the costs per unit length for very short length conveyors are very high, as would be expected. For the zero slope case (Figure 9) and for the range of lengths beyond 200 m, the costs per unit length are substantially constant. This trend is also shown to occur for the slope of 1 in 10 (Figure 10) for the narrower belts, but as the belt widths increase, the cost per unit length starts to increase with belt length. Furthermore, the belt length becomes restricted due to the limitations in plies. A stronger belt would then be necessary. For wider belts the indications favour the use of several short conveyors rather than one long belt. However, the cost advantage in employing several conveyors would be either partially or totally offset by the additional costs due to the transfer stations.

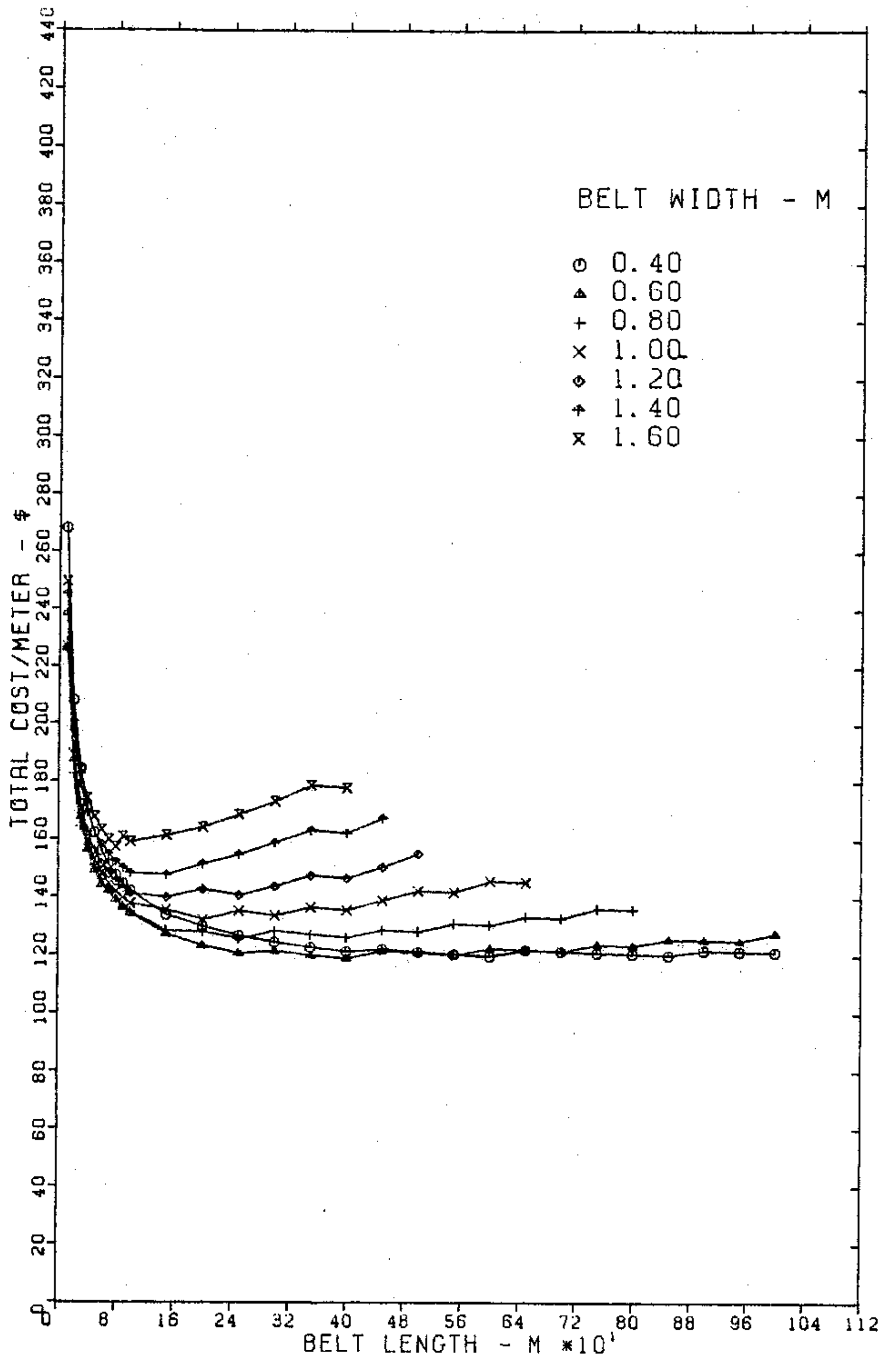
As shown by Lim [10], the optimum number and length of component conveyors may be determined as part of the solution to the general belt conveyor design problem. Solutions to such problems have been obtained using the Box (complex) algorithm. One example considered by Lim involved the requirement to convey a bulk material of density $\rho_m = 800$ kg/m^3 over a distance of 5 km up a slope of 1 in 100. It was assumed that the component conveyors were all of equal length and constraints were imposed to limit the number of plies to 8, the belt speed to 6 m/s and the minimum belt width



BELT CONVEYOR - TOTAL COST PER METER -

Q= 600 T/HR, SLOPE 0.0

<u>Figure 9</u>



BELT CONVEYOR - TOTAL COST PER METER -

Q= 600 T/HR, SLOPE 0.1

Figure 10

to 0.75 m. Considering the overall costs, including the structure but neglecting the transfer stations, gave the optimum solution

Number of belt sections	N	=	11
Belt width	B	=	0.75 m
Number of plies	p	=	2
Belt speed	v	=	3.27 m/s

If the cost of transfer stations is included, the number of belt sections decreased to N = 3, and number of plies increased to p = 6. The other parameters remained unchanged.

8. CONCLUSIONS

This paper has drawn attention to the costs of bulk handling operations and the consequent need to design more efficient and economical systems. To achieve this objective a design methodology has been developed which integrates the underlying principles of engineering economic analysis with the concepts of optimization theory.

The paper has dealt specifically with the economic analysis and optimum design of belt conveyors for bulk solids handling. The various conveyor component costs as functions of the overall costs have been examined and the conclusions drawn favour the use of narrower, faster-running belts. Analysis of annual equivalent costs per unit length has provided guidelines for the selection of optimum lengths of conveyors in multi-conveyor systems.

On the basis of the design and analysis procedure presented, comparisons between various types of conveyors can readily be made. It is clear, from the results presented, that the global problem of optimization applied to large, integrated handling systems can only be meaningful when the best operating conditions of individual conveyors and other items of handling equipment are understood.

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APPENDIX

Calculation of Annual Equivalent Cost Coefficients. Example - Coefficient for Belt Cost, k_4.

Assumptions

Capital is all equity capital, that is $r_d = 0$

Required return on equity, $i_e = 5\%$

Income tax rate, $t = 46\%$

Conveyor system life, $n = 12$ years

Estimated belt life = 7 years

General inflation rate $r = 10\%$

Annual cost excalation rate of belt $r_b = 15\%$

Salvage value at any time, $V = 0$

Depreciation by straight line based on 7 year life with remaining value written off at the end of year 12

$$i_f = (1-t)\ r_d i_d + (1-r_d)[(1+r)(1+i_e) - 1]$$

$$= 0 + (1+.10)(1+.05) - 1$$

$$= 0.155$$

$$i_f^o = \frac{(1-t)\ r_d i_d - rr_d}{1+r} + (1-r_d)\ i_e$$

$$= 0 + 1(.05)$$

$$= .05$$

Price of replacement belt $= A(1.15)^7$

Present equivalent of first cost of belts $= A[1 + (\frac{1.15}{1.155})^7]$

$= 1.9701\ A$

Depreciation of first belt $= \frac{A}{7}$ each year for seven years

Depreciation of second belt = $\frac{A}{7}(1.15)^7$ each year plus an additional $\frac{2A}{7}(1.15)^7$ in year 12.

$$PED = \frac{A}{7}\left(\frac{p}{a}\right)_7^{i_f} + \frac{A}{7}(1.15)^7 \left(\frac{f}{a}\right)_5^{i_f} \left(\frac{p}{f}\right)_{12}^{i_f} + \frac{2A}{7}(1.15)^7 \left(\frac{p}{f}\right)_{12}^{i_f}$$

$$= A\left[\frac{(1.155)^7 - 1}{(7)(.155)(1.155)^7} + \frac{(1.15)^7}{7}\left(\frac{1.155^5 - 1}{.155}\right)\frac{1}{(1.155)^{12}} + \frac{2}{7}(1.15)^7 \frac{1}{(1.155)^{12}}\right]$$

$$= A\,[.5855 + .4591 + .1348]$$

$$= 1.1794A$$

$$PEC = \frac{A - V\left(\frac{p}{f}\right)_n^{i_f} - t(PED)}{1-t}$$

$$= \frac{1.9701A - .46(1.1794A)}{.54}$$

$$= 2.6436A$$

$$AEC = PEC\left(\frac{a}{p}\right)_{12}^{5}$$

$$= (2.6436)(.11283)A$$

$$= .2983A$$

Thus the annual equivalent cost coefficient

$$k = \frac{AEC}{A} = 0.2983$$