EVOLUTIONARY BELT CONVEYOR DESIGN

Craig Wheeler and Daniel Ausling

INTRODUCTION

Belt conveyor systems have very few rivals in terms of efficiency and throughput for a continuous bulk solids transportation system. They are by far the most widespread transportation system used across the mining and mineral processing industries. Consequently, the efficient design and operation of belt conveyors can have significant impact on the productivity and viability of these important industries. For this reason, the research presented in this paper focuses on improving the efficiency and reducing the cost of these systems through the use of numerical evolutionary optimisation methods during the design process.

Belt conveying technology has dramatically changed over the last two decades resulting in longer conveyor installations running at faster belt speeds. As conveying distances and belt speeds increase it is becoming increasingly important that these systems are designed for optimum efficiency by reducing motion resistances and selecting design variables that reduce the overall cost of the system. With these objectives in mind, the work presented in this paper represents the initial findings of an ongoing research project aimed at optimising conveyor design. The research project is funded for a period of 3 years by the Australian Commonwealth Government under the Australian Research Council (ARC) Discovery Projects Scheme.

The work involves utilising models to predict the motion resistance of belt conveyors that take into consideration the influence of variables, such as idler roll diameter and spacing, troughing configuration, belt speed and cover properties, and bulk material properties. Given a specified conveyor configuration the capital and ongoing costs of the system can then be calculated based on the required belt strength and width, structure, drive, etc. The research provides a computational means to analyse a wide variety of potential conveyor configurations and to compare each in terms of cost. Numerical evolutionary optimisation methods are then employed to determine the best solution in terms of annual equivalent cost.

The basis of the optimisation method involves accurately calculating the motion resistance of the belt conveyor. The motion resistances that occur along the length of the conveyor are known as the main resistances and include the effects of the belt and bulk solid flexure, the rotation of the idler rolls and the indentation of the idler rolls into the rubber belt. Work by Wheeler [1] provides computational methods for calculating each of the main resistances using measurable conveyor belt and bulk solid properties. This provides the opportunity to optimise belt conveyor designs for energy consumption and costs. However, due to the complex interrelation between conveyor variables the objective to optimise the selection of these variables is not straightforward. For example, reducing the idler spacing has non-linear effects on the belt and material flexure resistance, the idler rotation resistance per unit length, and the indentation rolling resistance per idler roll due to the change in load.

To undertake this complex optimisation problem, computational methods that draw their paradigm from biological evolution have been adapted to the process of belt conveyor design. The initial population of potential conveyor configurations (idler roll diameter, spacing, belt speed, etc) is randomly generated (within upper and lower boundaries). The designs are then evaluated using a fitness function to evaluate the annual equivalent cost of the system. Systems that perform well are used to generate (or breed) a new population, passing on their selected variables (or genes) to the next generation with small induced modifications or “mutations”. The process of evaluating and breeding is repeated until a range of optimal solutions is obtained.

The application of computational optimisation methods to belt conveyor design was first undertaken by Roberts et al [2,3]. This work provided a detailed economic analysis of belt conveyor systems based on life cycle costs. Cost functions were derived to take into consideration the energy costs and annual equivalent costs of conveyor components for the design life of the system. Component life, salvage value, taxation rate, and rate of return were considered. Optimum designs for a minimum annual equivalent cost were determined based upon performance and, geometric and design constraints. The analysis was undertaken using a modified ISO5048 method and, as such restricted the range of variables that were able to be optimised. The work presented in this paper couples the economic analysis of Roberts et al [2,3] with the motion resistance models of Wheeler [1] and applies state-of-the-art evolutionary computational methods to undertake the optimisation process.

EVOLUTIONARY METHODS - AN INTRODUCTION

Evolutionary computational methods imitate biological evolution in order to find optimum solutions to complex problems that typically involve many variables. The general framework of the various evolutionary techniques is essentially the same and can be summarised as follows (Beyer et al [4])];

1. An initial population of potential solutions (known as individuals) is randomly generated.
2. The individuals in the population are evaluated using the objective function (known as fitness).
3. Individuals who perform well are used to generate (or breed) a new population, passing on their genes to the next generation with small induced errors or “mutations”.
4. Iteration over steps 2 and 3 is carried out until the population converges to an optimal solution.

The primary advantage of using this type of optimisation strategy is to remove any human bias that may be introduced. Additionally, to arrive at an optimal solution may involve the evolution and evaluation of many thousands of potential conveyor configurations which only a computational method can efficiently and “sanely” undertake.

Evolutionary methods are currently used in many areas to solve complex optimisation problems, such as wind turbine blade design, air traffic control, structural optimisation and timetabling. Recent work by Wensrich [5] and, Wensrich and Wheeler [6] has proven the significant potential of such optimisation methods to the design of conveyor transfer chutes. This work involved single-objective evolutionary methods applied to conveyor loading chute design. The work provided a means to achieve optimum performance with minimum chute wear as well as minimum belt wear at the loading point.

EVOLUTIONARY METHODS APPLIED TO BELT CONVEYOR DESIGN

The optimisation of belt conveyor systems is undoubtedly a complex problem. The difficulty arises from the many non-linear interrelations between the design variables and the objectives. The design variables in the present analysis have been limited to the belt width, idler roll diameter and spacing, while the objective is to minimise the annual equivalent cost of the system.

The problem involves working with a mixture of discrete and continuous variables that each influence the objective function to varying degrees. For example, conveyor belting is restricted to set widths and incremental tensile strengths. Similarly, idler roll diameters are constrained to a series of sizes governed by the standard pipe diameters from which they are manufactured. Conversely, idler spacing and belt speed can take any conceivable value within practical limits. Furthermore, considering the objective function, varying something as simple as idler spacing influences not only the annual equivalent cost of the idler rolls and frames, but also the annual equivalent cost of belting due to variations in belt tension and the annual energy cost. For example, a reduction in idler roll spacing will influence the belt and bulk material flexure resistance, the idler rotation resistance per unit length, and the indentation rolling resistance per idler roll due to the change in load. This interrelation of variables is clearly complex, making the optimisation problem far from straightforward.

To overcome this difficulty, evolutionary strategies have been employed that use both discrete and continuous variables. Each individual, or potential solution, is represented by a vector that contains all of the variables that are to be optimised in the final design. For example, the first element in the vector contains the value of the belt width, while the second identifies the idler roll diameter and the third element the spacing of idler roll sets.

The process begins with the user entering the performance requirements of the system, such as transport distance, throughput, estimated hours of operation per annum and design life of the system. The bulk density, surcharge angle and internal friction angle of the bulk material are also entered into the program. The program uses pre-calculated data for the belt and bulk material flexure resistance, and the indentation rolling resistance. This data is generated in computational methods developed by Wheeler [1] and accessed by the optimisation program through linked data files.

With reference to the general framework of evolutionary techniques mentioned earlier, the optimisation process begins by seeding an initial population of potential solutions (known as individuals) by randomly selecting values for each of the design variables. Initial work has involved optimising belt width, idler roll diameter and idler roll spacing. Typically the population consists of more than 1000 randomly generated potential solutions with variables selected between either set or user defined boundaries. For example, belt widths and idler roll diameter are restricted to industry standard sizes. While idler spacing and belt speeds can take on any conceivable value, but can be limited depending on the properties of the bulk solid, such as particle size range, process requirements, etc.

The individuals in the population are then evaluated using the objective function to determine their relative performance (known as fitness). The objective function that evaluates the annual equivalent cost of the conveyor systems takes into consideration the annual energy cost and annual equivalent costs of conveyor components for the design life of the system. The objective functions were derived from the work of Roberts et al [2,3] and take into consideration component life, inflation, taxation rate and rate of return.

In the present analysis component life is determined using the methods described by Roberts [3]. In this work it is assumed that the all components, excluding the idler rolls, last the life of the installation. However in saying this, the introduction of individual design lives for all components is easily integrated into the program, providing component life can be quantified. The program currently uses the work of Jilek [7] and Rozentals [8] to determine the expected life of the idler rolls. This research shows that for an idler roll operating under favourable environmental conditions the life of the roll is governed by the fatigue life of the bearings. The time in hours for the first 10% of centre idler rolls to fail L_c, is given by:

$$L_c = \frac{0.4974D}{v}\left(\frac{P_r}{P_a}\right)^{\mu} \tag{1}$$

While the time in hours for the first 10% of troughing idler rolls to fail L_t, is given by:

$$L_t = \frac{0.8552D}{v}\left(\frac{P_r}{P_a}\right)^{\mu} \tag{2}$$

Where: D = Idler roll diameter [mm]
v = Belt speed [m/s]
P_r = Rated bearing load [N]
P_a = Actual bearing load [N]
μ = 3.0 for ball bearings and 3.3 for roller bearings

Based on Eqns (1) and (2) the total number of idler rolls required to be replaced in each year of operation can be calculated and therefore added to the annual equivalent cost of the initial rolls calculated over the life of the installation. The relationship also shows that for a given loading ratio (P_r/P_a) the life of idler rolls is proportional to the roll diameter and inversely proportional to belt speed.

The annual energy cost is calculated using the motion resistance models of Wheeler [1]. These models calculate each component of the motion resistance and compare well with typical resistance breakdowns documented by Hager and Hintz [9]. The basis of the resistance models can be summarised as follows:

- Resistance due to rotation of the idler rolls. This model calculates the viscous drag due to the shearing of the grease within the labyrinth seals, the friction torque of the rolling bearings generated from the no-load and load dependent moments, and the rotating resistance of the contact lip seals.
- Resistance due to flexure of the belt and bulk material. This model uses plate theory to approximate the deflection of the belt between idler sets, whereby resistance is calculated through hysteretic losses in the belt and the work done in deforming the bulk material through active and passive stress states.
- Resistance due to indentation rolling resistance. This model uses a linear viscoelastic finite element method to calculate the hysteretic losses due to the continual deformation and relaxation of the rubber cover as it passes over the idler rolls.

The sum of all of these resistances over the length of the conveyor determines the total motion resistance, which is used to estimate the power requirements of the installation and thus the annual energy cost.

Individuals who perform well, that is have a low total annual equivalent cost, are then used to generate (or breed) a new population, passing on their design variables (genes) to the next generation with small induced errors or “mutations”. As noted by Wensrich and Wheeler [6], the breeding method must satisfy two competing objectives, these are to produce offspring with low annual equivalent cost in the image of their parents, and provide enough diversity to explore a wide range of the gene space and avoid local maxima and minima. For this reason, the breeding method chosen selects the best solutions (individuals) from the population and breeds them randomly by simply averaging their genes. The best solutions are returned to the population to ensure the maximum fitness does not decline and, to ensure the gene pool is fully explored random mutations are also made to the new solutions.

The number of individuals returned to the population, offspring, mutations and size of mutation are each set by the user. The process of evaluation against the objective function and breeding new solutions is repeated until the population converges to an optimal solution. The potential conveyor configurations are ranked according to the fitness of each, or in other words, compared and ranked according to their total annual equivalent cost. Design data for the optimum conveyor configuration is then made available for the user, along with the calculated annual equivalent cost for each major component.

The program is coded in Fortran 95 and operates on a personal computer. Computation time for a typical population of 1000 individuals is currently less than 1 minute on a Pentium 2GHz processor with 1GB of RAM. As the number of variables increase with further development of the program the computation time is not expected to exceed 1hr. However, in saying this these times are based on the optimisation process alone. The input data for the bulk material flexure resistance and the indentation rolling resistance takes approximately 1 week to generate on a cluster of 5 x Pentium Dual Core, 2GHz processors each with 1GB of RAM. The computation time depends on the range of variables to be analysed.

RESULTS AND DISCUSSION

While the program is in the early stages of development, the results to date have provided useful insight into the driving factors behind reducing the costs of belt conveyor systems. Earlier work undertaken by Roberts et al [2,3] clearly identified the economic benefits of faster narrow conveyor belts. This work identified belt widths between 600mm to 1000mm to give the lowest annual equivalent cost for the life of the plant. Results to date have mirrored these findings, with the added advantage of also being able to determine optimum idler spacing and roll diameters. Additionally, the program also provides optimum conveyor configurations based on measured bulk material and conveyor belt properties.

As mentioned in the previous section, the optimisation program accesses pre-calculated data for the belt and bulk solid flexure resistance and the indentation rolling resistance. This option was chosen to reduce the computational time of the optimisation process, since the numerical methods that calculate the motion resistance components are computationally intensive, involving iterative finite element and finite difference methods where the computational times are typically measured in hours. Consequently, rather than having to run these programs for each individual in the population when evaluating their fitness against the objective function, the pre-calculated data provides much quicker data access, greatly reducing total computational time.

Calculating the bulk solid flexure resistance data involves analysing a variety of belt widths and speeds, idler roll spacings and sag ratios. The flexure resistance occurs due to the difference in work done between the opening and closing of the belt between successive idler sets. As the belt progresses from one idler set to the next the bulk solid undergoes cyclic expansion and contraction in the transverse direction, in addition to variation in height in the longitudinal direction. As the belt opens the bulk material supported by the outside idler rolls dilates and experiences an active stress state, while as the belt approaches the next idler set the material is compressed as the belt closes and is subject to a passive stress state. The material supported by the centre idler roll undergoes the opposite stress states. This relative movement results in energy loss known as bulk material flexure resistance.

The bulk solid flexure resistance is calculated based on the properties of the bulk material, including bulk density, conveyor surcharge angle and internal friction angle. Given these inputs the bulk solid flexure resistance is calculated for a range of idler spacings, belt speeds, belt widths and sag ratios. The flexure resistance values are then stored in a 4-dimensional array which the optimisation program accesses. When individuals in the population have variables which lie between calculated values the optimisation program interpolates between these values to estimate the flexure resistance. For example, as the belt sag varies along the length of the belt with belt tension, the program interpolates between calculated sag ratios to determine the corresponding change in bulk material flexure resistance.

Figure 1 shows data for a bulk material with an internal friction angle $\phi_i = 35^o$, bulk density $\rho = 1000 kg/m^3$ and conveyor surcharge angle $\delta = 20^o$. The centre and outside idler rolls are set to be equal length and the troughing angle β is fixed at 35^o. Results clearly demonstrate the variation in bulk material flexure resistance with each variable. The data presented in Figure 1 shows typical trends for the bulk material flexure resistance component. For example, increasing sag ratio results in bulk material undergoing greater relative movement, therefore resulting in increasing bulk material flexure resistance. Similarly, increasing belt width also results in greater flexure resistance due to more material being displaced. While increasing belt speed results in greater flexure resistance due to the transition between the active and passive stress states occurring closer to the next idler set resulting in more work being done. A detailed explanation of the influence of each of these variables and related trends is given by Wheeler [10].

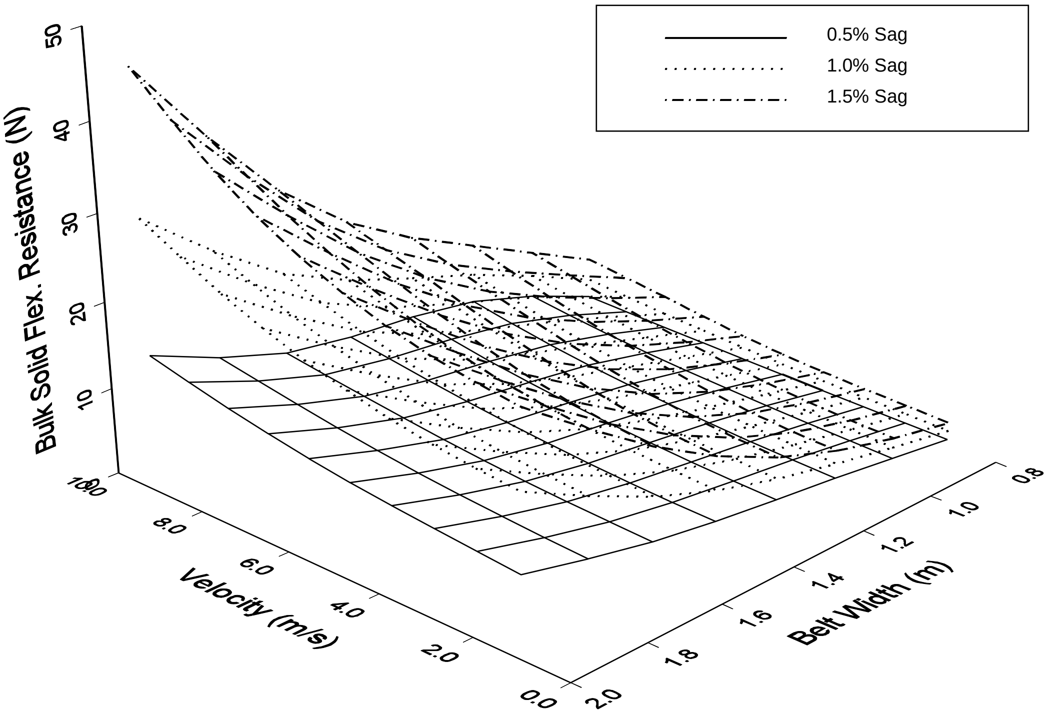

Fig. 1: Bulk material flexure resistance verses belt width and velocity for a range sag ratios. Internal friction ϕ_i = 35°, Bulk Density ρ = 1000kg/m^3, Surcharge Angle δ = 20°, Troughing Angle β = 35°.

Figures 2(a) and 2(b) show typical data generated from the indentation rolling resistance program. The data presented are for simulations conducted at 20°C with an SBR (Styrene Butadiene Rubber) bottom cover compound. Results show the indentation rolling resistance verses load and velocity for idler roll diameters of Ø127mm and Ø178mm. Unlike the bulk solid flexure resistance data, functions for the indentation rolling resistance verses normal load are derived directly from the linear viscoelastic finite element analysis. The functions are derived for a range of idler roll diameters and belt speeds. Since the roll diameter can only take on discrete sizes, interpolation is only required for variations in belt speed. Like the bulk solid flexure resistance analysis, the use of pre-calculated data greatly reduces computational time by not having to run the computationally intensive viscoelastic finite element analysis for each individual in the population.

The results presented in Figures 2(a) and 2(b) highlight typical trends. Data shows increasing normal load results in a non-linear increase in indentation rolling resistance, while increasing belt speed results in an increase in indentation rolling resistance that tends to plateau at higher belt speeds. Additionally, increasing idler roll diameter results in a reduction in indentation rolling resistance.

The indentation rolling resistance is calculated for each idler roll set and is summed along the length of the conveyor for both the carry side and return side. The load distribution across the idler sets on the carry side is calculated from the bulk material flexure resistance program, while the return side is calculated due to the weight of the belt. Given the normal load the indentation rolling resistance is then calculated by integrating across the width of the belt.

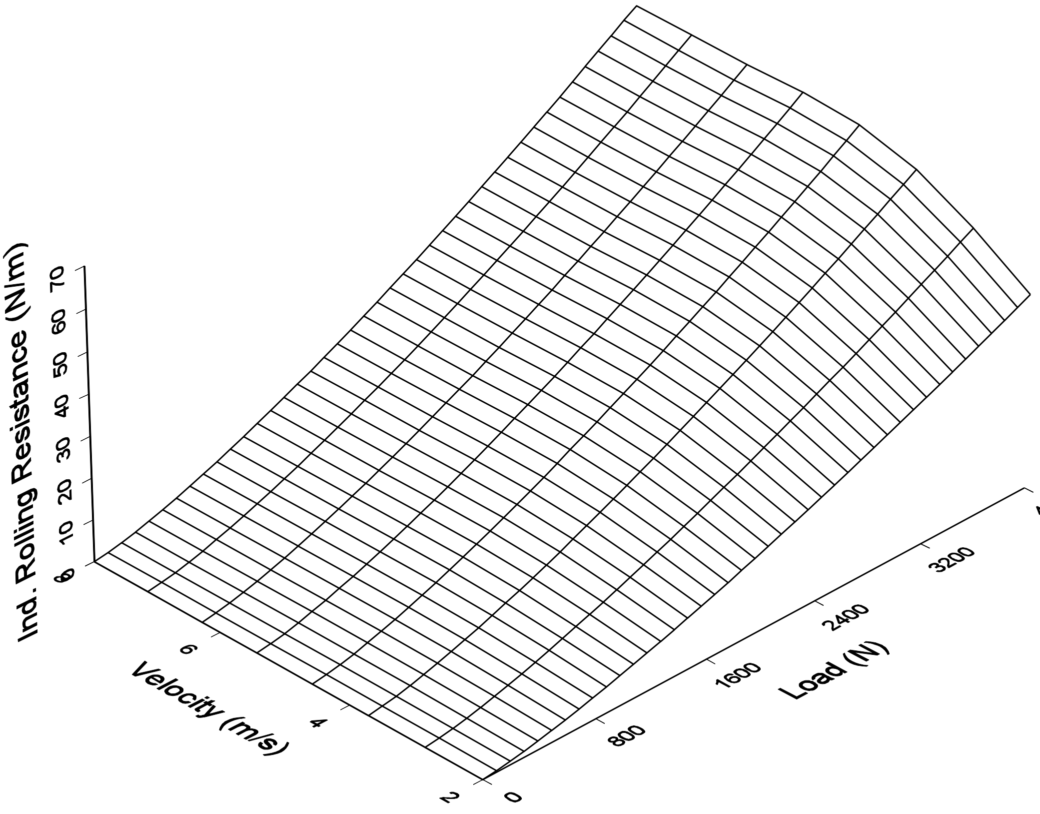

Fig. 2(a): Indentation rolling resistance verses load and velocity for a Ø127mm idler roll.

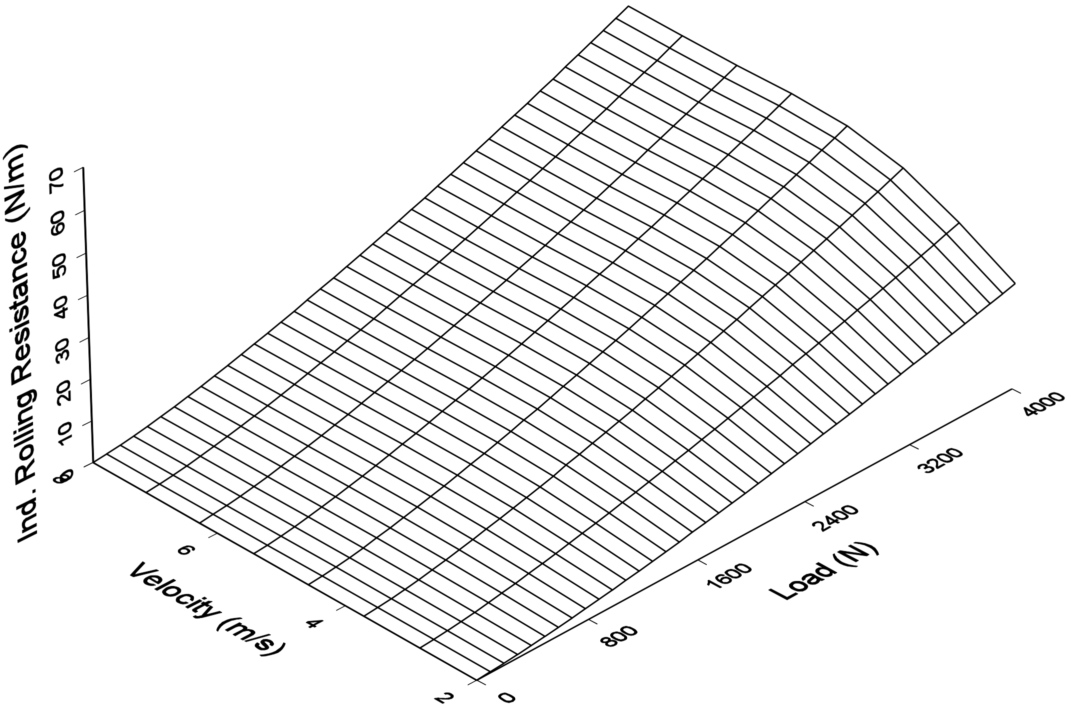

Fig. 2(b): Indentation rolling resistance verses load and velocity for a Ø178mm idler roll.

The flexure resistance of the conveyor belt is calculated through hysteretic losses in the belt derived from the relative belt movement. The belt flexure resistance is calculated in the same computational method that calculates the bulk material flexure resistance. The only remaining component of the motion resistance is the idler rotating resistance, which is calculated within the optimisation program. This model calculates the viscous drag due to the shearing of the grease within the labyrinth seals, the friction torque of the rolling bearings generated from the no-load and load dependent moments, and the rotating resistance of the contact lip seals. The rotating resistance is a function of the idler roll diameter, bearing type and size, belt speed, loading and temperature. The calculation procedure is not computationally intensive and is therefore incorporated into the optimisation program.

The total motion resistance is calculated by summing each of the individual motion resistance components along the length of the conveyor. The annual equivalent energy cost is then calculated based on the belt speed. The remaining annual equivalent costs consist of major component costs, including the structure, belt, idler rolls and frames, drives, etc. These component costs are determined as functions of the relevant conveyor variables. The cost functions of the major components are derived from the work of Roberts et al [2,3].

To demonstrate the optimisation process, consider a belt conveyor 2km long, with a throughput of 1500t/hr, transporting bulk material with the constraints and properties shown in Figure 1, and belt properties detailed in Figure 2. The optimised solution is a conveyor with a belt width of 800mm, operating at 5.8m/s with idler roll diameters of 178mm at a carry side spacing of 3.6m. Figure 3 shows the variation in annual equivalent cost with idler spacing around the optimum value of 3.6m. As idler spacing increases the belt cost tends to dominate the annual equivalent cost due to the requirement of higher strength belting which is more expensive. Closer idler spacings see the cost of idler rolls and frames dominate costs.

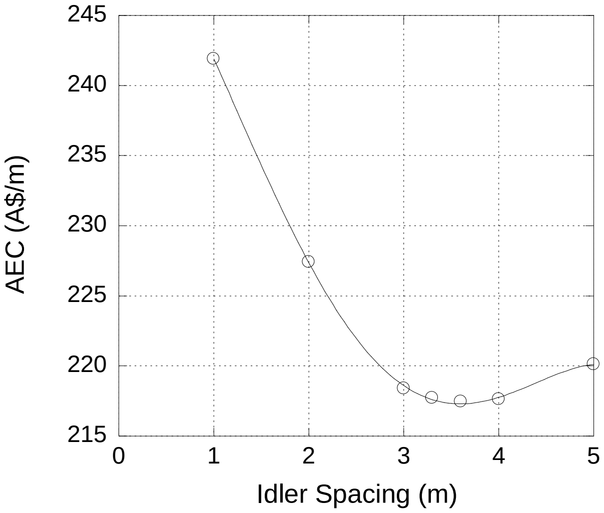

Fig. 3: Idler spacing optimised to minimise annual equivalent cost (AEC).

Figure 4 is included for comparison to show the influence of motion resistance. The plot of motion resistance and equivalent friction factor verses idler spacing shows that 2.0m is the optimum idler roll spacing to minimise motion resistance for this particular installation. The results were obtained by fixing the belt width at 800mm and the belt speed at 5.8m/s. Comparing the two graphs highlights that the increased energy and belt costs resulting from the slight increase in motion resistance and belt tension at 3.6m idler spacing is offset by the cost of idler rolls and frames in this particular case.

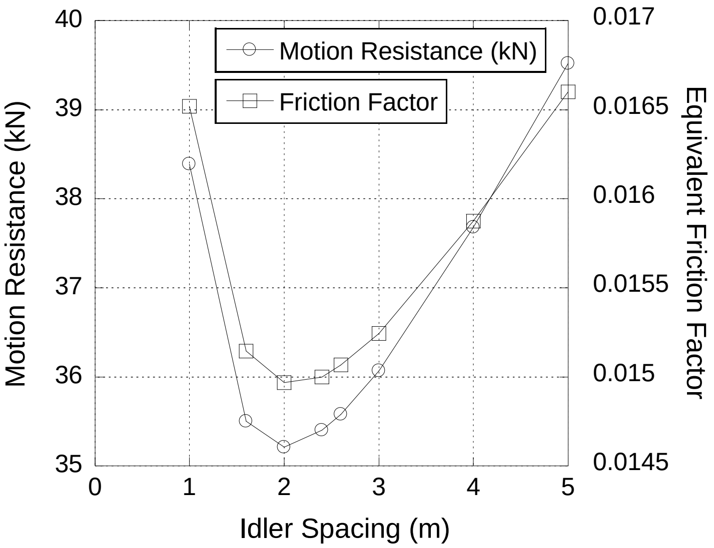

Fig. 4: Idler spacing optimised to minimise motion resistance.

The process of optimising the belt width is also noteworthy of discussion. The work of Roberts et al [2,3] identified clear economic benefits of faster narrow conveyor belts. The results presented in Figure 5 support these findings, showing a decreasing annual equivalent cost with reducing belt width. While the results indicate that even narrower belts would reduce the annual equivalent cost of the system, in this particular case an upper limit was placed on the belt speed which effectively set a minimum belt width. The program facilitates limitations and ranges to be placed on all variables to suit the particular constraints of the conveyor design. For example, limitations may be placed on belt speed due to bulk material properties such as particle size and percentage of fines and lumps, and process limitations such as loading and unloading constraints.

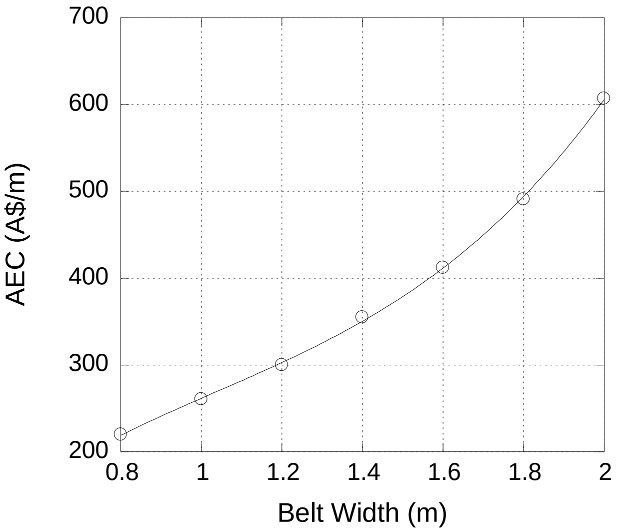

Fig. 5: Belt width optimised to minimise annual equivalent cost (AEC).

CONCLUSIONS

This paper presented an overview of an evolutionary optimisation process used to reduce the annual equivalent cost of belt conveying systems. Initial results are discussed which show good agreement with the trends identified by Roberts et al [2,3], with faster narrower belts clearly proving to be more cost efficient. The application of more rigorous motion resistance models in the current work provides the ability to optimise idler spacing and roll diameters. This facilitates the generation of optimum solutions based on measured bulk material and conveyor belt properties, leading to improved results.

While the program is in the early stages of development, the results to date have proven to be useful in gaining a better understanding into the driving factors behind reducing the costs of belt conveyor systems. Further variables will be optimised during the course of the project, including troughing angle, and idler length and diameter for the centre and wing rolls independently. Costing data is also an area that will be updated and enhanced with significant industry involvement and cooperation.

Overall the application of computational optimisation methods to belt conveyor design has proven to be a successful tool. The primary advantage of the application of these methods is the ability to evaluate many thousands of potential conveyor configurations without the preconceptions often imposed by human designers, while still being able to impose constraints to ensure the solution is practical.

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AUTHORS’ CV

Dr Craig Wheeler is a Lecturer in the School of Engineering at the University of Newcastle, Australia. He worked as a Mechanical Engineer for BHP Billiton for 11 years and then as a Research Fellow at the Centre for Bulk Solids and Particulate Technologies for 4 years. He was appointed as a Lecturer in Mechanical Engineering in 2002 and undertakes industrial consulting activities through TUNRA Bulk Solids Research Associates.

Mr Daniel Ausling is currently studying for a Bachelors Degree in Mechanical Engineering at the University of Newcastle. He is sponsored by TUNRA Bulk Solids Research Associates under the University of Newcastle Industry Scholarship Scheme (UNISS).