Condition-Based Conveyor Belt Replacement Strategy in Lignite Mines with Random Belt Deterioration

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Abstract. In Polish lignite surface mines, condition-based belt replacement strategies are applied in order to assure profitable refurbishment of worn out belts performed by external firms specializing in belt maintenance. In two of three lignite mines, staff assess belt condition subjectively during visual inspections. Only one mine applies specialized diagnostic device (HRDS) allowing objective magnetic evaluation of belt core condition in order to choose the most profitable moment for the dismantling of worn out belt segments from conveyors and sending them to the maintenance firm which provides their refurbishment. This article describes the advantages of a new diagnostic device called DiagBelt. It was developed at the Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology. Economic gains from its application are calculated for the lignite mine and for the belt maintenance firm, taking into account random life (durability) of new and reconditioned belts (after the 1st and the 2nd refurbishment). Recursive calculations for following years allow the estimation of the length and costs of replaced, reconditioned and purchased belts on an annual basis, while the use of the Monte Carlo method allows the estimation of their variability caused by random deterioration of belts. Savings are obtained due to better selection of moments (times) for the replacement of belt segments and due to the possibility to qualify worn out belts for refurbishment without the need to remove their covers. In effect, increased belt durability and lowered share of waste belts (which were not qualified for reconditioning) create savings which can quickly cover expenditures on new diagnostic tools and regular belt inspections in the mine.

1. Introduction – random factors influencing belt deterioration

The process of wear and tear in conveyor belts is influenced by many factors, most of which have a random character. These factors may be divided depending on:

- the transported mined material (the distribution of lump sizes in the stream of fed mined material [1, 2], abrasiveness of the mined material, edge sharpness, density, internal friction, etc.),
- the design of the feeding and transfer points (e.g. drop height of the fed material, drop energy and acceleration energy, the design and the installation of energy-absorbing devices), [3, 4],
- belt type (textile, steel-cord, solid woven) and materials used in the belt (various types of textile fabrics, steel cords, kevlar/aramid [5]) and the presence or absence of different breakers (e.g. textile, wires) [6],
- rubber parameters (abrasiveness, hardness, strength parameters),
• conveyor design (length [7], idler spacing [8, 9], belt speed, tensioning) and ancillary equipment used (for belt scraping, training, diagnostics, etc.),
• technology used in the operation of the conveyor system, which typically results from the technology used in the mining operations (loading cycles, variable loading, etc.) [10, 11],
• transportation conditions and their variability (temperature, humidity, changes of the conditions) [12, 13],
• the quality of maintenance and service works performed on belts and splices and care exercised during their operation [14].

2. The influence of “local” and “linear” factors on belt life
Conveyor length is one of the factors whose influence on belt life has been well investigated. Publications [e.g. 15-17] classify the factors which influence belt wear into “local” and “linear” factors (figure 1). The linear factors have an influence on the belt along the complete route of the conveyor (they are proportional to the distance travelled by the belt) and have a gradual character – they accumulate as the belt passes on the conveyor).

![Graph showing the variation of percentage contribution of “local” and “linear” damaging agents in conveyor belt wear process as a function of conveyor length in two periods: in the 1980s (dotted line) and currently (solid line) [18].](image)

Figure 1. Variation of percentage contribution of “local” and “linear” damaging agents in conveyor belt wear process as a function of conveyor length in two periods: in the 1980s (dotted line) and currently (solid line) [18].

“Linear” factors cause the abrasion of the rubber covers and the damage of belt edges. Also, they stimulate fatigue processes which occur in the core of the belt due to the bending of the belt on idlers and to the changes in belt geometry that lower core strength. “Local” factors are concentrated in a single location (e.g. at the feeding point, on the drive and tail pulleys and at those points along the conveyor route where various devices are installed). The results of the above factors, both the accumulating ones (inter alia cover abrasion due to the acceleration of the transported material or to friction against the sealing devices of the feeding hoppers, increasing number of cover and corer punctures, or fatigue processes in the core due to the wrapping of the belt around the pulleys), and the single, often catastrophic ones (inter alia belt cuts, torn out cords or ruptured covers) are proportional to the number of cycles. Both the “linear” and the “local” factors are random and result from a stochastic nature of mined material, as well from the operating conditions, the design and the quality of the belt and the conveyor. Their share may be estimated, however. Interestingly, this share remains stable even though the durability of belts increased significantly since the 1980s (figure 2) [18].
Figure 2. Changes of belt durability in a copper ore mine measured by the number of cycles \( n_c \) and calendar time \( T_t \), as a function of conveyor length \( L_p \) (and belt speed \( v \)) in two periods: in the 80s (dotted line) and at present (solid line) [18].

With the development of modern diagnostic tools which allow the evaluation of belt condition (its core [18], belt edges, cover abrasion degree, changes in splice lengths [19-21], etc.), new possibilities emerge for a more accurate description of the belt degradation process and for the quantification of its changes in time. The verification of the intuitively and theoretically suggested relationships may be now shifted from the qualitative level to the quantitative level and may also be done using measures of wear degree which are significantly more precise than the calendar time of operation for the belt segments to be replaced. It is now also possible to more precisely estimate the effects of “linear” and “local” factors, by determining the rate of cover and edge abrasion, the rate at which new defects occur and the distribution of defects on the belt.

3. The potential of the Diagbelt system

The Diagbelt system [22] has been developed at the Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, as part of an NCBiR research grant, and functions as a magnetic module in an intelligent, integrated system for the diagnostics of conveyor belts [23]. It is equipped with the BeltGuard measuring bar, manufactured by BeltScan – an Australian company specializing in belt diagnostics since the 1970s. The compressed digital signal obtained from a mobile measuring head comprising 112 sensors (without the neutral zeros describing the undamaged belt fragments) is imported into a self-developed application called Diagbelt, and serves as the basis for the analysis of the condition of a complete belt loop and its individual sections and splices. The software is a successor to the HRDS system, which was implemented in one of Polish lignite mines and was based on the EyeQ measuring bar [24]. The high resolution measuring head of the new system (2.5 cm wide measuring track) offers improved damage imaging and allows the representation of defects on a 2D plane (figure 3) along with the traditional single-dimensional signal known from a number of other magnetic systems with wide measuring circuit (up to 40 cm). Additionally, several scans of the belt allow a three-dimensional damage representation which shows not only the X,Y location of the defect, but also signal intensiveness in the area of defect (figure 4). The Diagbelt system also offers an original, own 2.5D imaging method. The belt is divided into 10 cm by 10 cm squares and mean damage intensity calculated for each of the squares is represented with a color, while the color of a point placed in the central part of each square corresponds to the maximum signal level on the area (figure 5). Such method allows avoiding perspective and as a result provides a more precise representation of signal level and its...
location. Aggregation to 10x10 cm squares does not decrease the resolution significantly (one square is covered by 4 measuring tacks), but instead ensures a more accurate identification of areas requiring repair, since it corresponds well to the typical size of repair (patch). At the same time, a high resolution 2D image allows identifying the size of a defect and, after more scans, calculate the rate of damage area growth in the belt’s longitudinal axis and transverse direction (figure 3).

Figure 3. 2D image of belt defects with one defect zoomed and dimensioned, and a traditional 1D signal (sum of all measuring tracks - the blue line above)

Figure 4. Image of a splice (3D) with an explanation of how the signal intensiveness is identified on the system’s various sensitivity levels.

Figure 5. 3D and 2.5 images of the same splice between two belt segments. Below: 1D signal (left side) and the key to the colors used (right side) [25].
4. Radom deterioration of belts and its impact on savings due to application of belt diagnostics

Conveyor belt reconditioning has been provided in lignite mines in Poland for about fifty years. In the mid-1960s, the first belt reconditioning plant was established in the “Turow” lignite surface mine. Then, in the mid-1970s, the next facility was launched in the Konin lignite mine and in 1981 the Belchatow lignite mine started to refurbish conveyor belts. Belt reconditioning is nowadays still carried out in the Turow and the Belchatow mines. Both plants belong to the Bestgum firm created by PGE (electric energy producer who owns lignite mines) in order to provide maintenance services of conveyor belts used in both mines as well as in external companies (e.g. the Konin lignite mine, which belongs to another electric energy producer ZE PAK SA).

All three Polish lignite mines apply a belt replacement policy which takes belt condition into consideration and ensures cost-effective belt refurbishment. A belt segment operated on a conveyor is replaced when its failure occurs or when the belt’s condition reaches a point beyond which cost-effective refurbishment is impossible. The disassembled belt segments are sent for reconditioning. In order to choose the most profitable moment for belt replacements, application of specialized diagnostic devices is recommended (e.g. DiagBelt system described in the previous chapter or similar systems [26]).

As regards the belt replacement policy focused on the cost-effectiveness of reconditioning, belt diagnostics may offer significant savings both to the mine (longer belt operating times) and to the company which services the transportation system (replacing belts, splicing and reconditioning disassembled belts), since financial losses due to reconditioning-related waste are reduced (as a result of more precise belt disassembly planning). This issue has been described in [27], based on mean operating times of belts. Further investigations should be aimed at determining whether the stochastic character of the changes in belt wear rate, as observed in various conditions and on various conveyors transporting coal or overburden, will have an influence on potential savings.

The iteration formulae provided in [27] allow identifying – based on mean belt operating times – the changes in the length of the different types of installed belts as well as in the replacement patterns of belts in successive years. These were shown in a hypothetical mine, where 100 km of conveyor belts are operated. New belts were assumed to have a mean life of 8 years, belts after first reconditioning – 7 years, and belts after second reconditioning – 6 years. The mean values are weighted average values for the life of coal belts, which constitute 1/3 of the total number of belts, and of overburden belts, which account for 2/3 of all belts. Belts used in transporting coal remain in operation for longer periods of time: 10, 9, and 8 years (new belts, after first and after second refurbishment, respectively), while belts transporting overburden material remain in operation for shorter periods: 7, 6 and 5 years, respectively. As a result, the assumed mean values were 8, 7 and 6 years. It was also assumed that the process of refurbishing new belts entails 10% of waste material (ON = 10%), and the refurbishment of belts after first refurbishment entails as much as 20% of waste material (OR = 20%). Belts after second reconditioning are not refurbished further, as practically all of them would fail the approval tests due to the reduced adhesion between the rubber and the cords and to the wear level of the core.

Using mean values may be a source of confusion, since actual situation may differ from the average. Therefore, the estimated potential savings should be represented probabilistically, so that their level calculated with deterministic methods does not generate overly optimistic expectations. To this end, mean values were replaced with random variables, which were matched with the distributions of operating times. Unfortunately, since open cast lignite mines did not provide any statistical data, calculations could not be based on actual data. Mines are extremely cautious about disclosing their sensitive data. It was assumed that the distribution of belt operating time until its disassembly for reconditioning takes the form of the Weibull distribution [28] with various alfa and beta parameters, selected so that the mean life values reached 10, 9 and 8 years respectively for new belts and for belts after first and second reconditioning (in the case of belts transporting coal) and 7, 6, 5 years respectively, in the case of belts transporting overburden. 1/3 of belts were assumed to transport coal and 2/3 – overburden. In order to determine mean belt operating times in a mine, 200 replacement procedures were simulated for belt sections having lives as presented above, and maintaining the proportions between replacements. In order to differentiate durability and conveyor lengths, the Weibull distribution
parameters were randomly selected from triangular distribution. All the parameters are presented in Table 1. An exemplary distribution is shown on figure 6.

**Table 1.** The parameters of Weibull distribution and triangular distribution (Δ), used in the simulation aimed at determining the variability of mean belt operating times in a hypothetical mine.

| Belt                | α – distribution Δ | β – distribution Δ | Upper and lower limits – distribution Δ |
|---------------------|--------------------|--------------------|------------------------------------------|
| Coal                | min. modal value   | max. min. modal value | max. min. modal value |
| New                 | 3 5 7              | 125 135 145        | 0 250 300 350          |
| After 1st R.        | 2.8 5 7.2          | 105 120 135        | 0 250 300 350          |
| After 2nd R.        | 2.4 5 7.6          | 85 105 120         | 0 250 300 350          |
| Overburden          | min. modal value   | max. min. modal value | max. min. modal value |
| New                 | 3 5 7              | 83 93 103          | 0 190 240 290          |
| After 1st R.        | 2.8 5 7.2          | 63 78 93           | 0 190 240 290          |
| After 2nd R.        | 2.4 5 7.6          | 47 67 87           | 0 190 240 290          |

**Figure 6.** Example, randomly selected Weibull density function (α = 4.287, β = 133.707 = 121.676 with an average = 121.676 months) for operating time of a new belt working in coal [29].

After 10 000 simulations of operating times were performed for each belt type, the data relating to the calculated mean values for the mine were transferred to the Stratigraphic application, which served to select the probability distribution for operating times. The results showed that the variability of mean values is best described with a normal distribution (N) having the following parameters:

- New belts: \( N (m = 98.019 \text{ months}; \sigma = 1.6964 \text{ months}) \),
- Belts after 1st reconditioning: \( N (m = 84.251 \text{ months}; \sigma = 1.50483 \text{ months}) \),
- Belts after 2nd reconditioning: \( N (m = 72.947 \text{ months}; \sigma = 1.39329 \text{ months}) \).

The selected parameters were used in the simulation of belt replacement and reconditioning in a model mine and were compared with deterministic results. As can be observed from the comparison (figure 7), the differences in the total belt length in relation to the deterministic data are practically negligible, since every year only slightly more than approx. 10% of belts are replaced. Therefore, random fluctuations of belt replacement procedures have only a limited impact on the total length of the installed belts. This can be clearly observed in the right-hand part of the figure: the replaced, purchased and reconditioned belts. The figure presents one of many possible future scenarios (one variant in the simulation).
Figure 7. Changes in the length of installed belts (new LN, after 1st reconditioning LR1, after 2nd reconditioning LR2), replaced belts (WN, WR1 and WR2), the newly purchased ones (ZN) and belts reconditioned (ZR) in successive years. The initial state is the same length of different belts (LN = LR1 = LR2 = 33 (3) km). Deterministic solution (top) [30] and stochastic solution (bottom) [31].

The changes in the average belt operating time have a more visible impact on the potential savings. Their variability is significant, since it is related on the one hand to the changes in yearly expenditures on purchasing new belts and reconditioning used belts and on the other hand – to the profits due to the increased durability. These were calculated proportionally to the mean operating time in a given year (increase by 10%), while the average values in the stochastic method were treated as random variables. The total changes accumulated, which had an effect on the significant observed increase in variability. The tendencies remain, however, as can be observed from the trend lines (figure 8) [31].

The level of potential savings grows significantly as the amount of material wasted during reconditioning procedures increases. The assumed range of material waste during reconditioning process: 10% and 20% levels of the material wasted during the first and the second reconditioning of belts, however, is overly optimistic, since the actual estimations point to 30% and 40% levels. With such levels of unsuccessful refurbishments, the generated savings may increase significantly. This applies to the increase in the revenue from reconditioning procedures, which almost triples. The savings in the mine also grow, since the number of newly purchased belts decreases, while the share of reconditioned, cheaper belts increases (this is based on an assumption that the cost of regeneration accounts for 60% of the cost of new belt [31]). The savings increase by approx. 200 000 pln per year in the system’s stabilization (homeostasis) period. Initially, however, they are higher (figure 9).
Figure 8. Potential savings in the mine and additional revenue of the belt servicing firm due to the reconditioning of belts which would normally be considered as waste, but were saved owing to the use of the diagnostic system, at 10% and 20% levels of the material wasted during the first and the second reconditioning of belts. Deterministic solution (left) [30] and stochastic solution (right) [31].

Figure 9. Potential savings in the mine and additional revenue of the belt servicing firm due to the reconditioning of belts saved owing to the use of the diagnostic system, at 30% and 40% of the material wasted during the first and the second reconditioning of belts. Deterministic solution (left) [30] and stochastic solution (right) [31].

The great amount of material wasted during refurbishment may result from cuts in the budget of the belt maintenance department. The operating time of belts increases, which leads to severe belt core defects. Since the changes in the condition of the cords in belt core are non-linear, extending belt operating time by a number of months does not produce any savings – the degradation in the core advances at a rate which is faster than linear and more belts are lost due to unsuccessful reconditioning than saved due to extended operating time.
Obviously, these reflections are hypothetical. The research methodology and IT tools (Excel spreadsheets with simulation models) have been prepared. In order to reflect actual data and not on hypotheses, it is only needed to use the statistical analyses of belt operating times to match actual distributions and actual belt waste indicators.

5. Conclusions
The here presented savings are only estimated, although effort was made to select realistic belt operating times and purchase costs. Therefore, the scale of potential savings should also be realistic. Allowing for the random variability of belt life until replacement enabled the representation of potential savings in probabilistic categories.

It was confirmed that the system tends to a state of equilibrium between the shares of each of the belt types in the total length of installed belts, and the length of both the replaced and newly purchased ones, i.e. the system’s “homeostasis.” The lengths of the different types of installed and replaced belts become stable on the level which reflects belt wear life and the amount of waste produced during refurbishment. On this occasion, however, in contrast to the solution based on mean parameters [1], significant fluctuations can be observed in the changes of the lengths of the installed and replaced belts and in the scale of potential savings over the successive years of mine operations. However, the selected trend functions confirm that the changes tend to the state of equilibrium known from deterministic solutions. Individual change trajectories may however deviate from the scenario developed using deterministic methods, which shows the risk.

The quantile scale of potential savings proves them to be sufficient to ensure a quick, even one year, return on the investment in diagnostic systems. Together with the production losses due to belt and splice failure, which could be avoided by using diagnostic systems, these results can only look more promising. The calculation of accurate savings is difficult, since mines are reluctant to provide their sensitive data. The scale of such savings is so great, however, that belt diagnostics is becoming increasingly popular worldwide and practically all larger belt manufacturers currently offer various solutions which aid belt monitoring. Unfortunately, these devices usually operate on-line on one conveyor, and therefore the scale of savings is limited as compared to a system in which a single device can be used to monitor many conveyors. Still, on-line devices may prove more effective at preventing failures than devices used in cyclical inspections.

Nevertheless, belt monitoring (continuous or cyclical) allows belt degradation processes to be monitored in various conditions, thus enabling the user to react more quickly to observed changes, to match belts to operating conditions and to prevent excessive belt damage. This means increased life, which also translates into significant savings. Hence, belt replacement times can be also predicted with greater accuracy, and belt fragments may be qualified for replacement in a way that minimizes transportation costs with no adverse effect on the reliability of the transportation system, much needed in such applications.

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