

Condition Monitoring of Rollers in Belt Conveyor Systems

Kammal Al-Kahwati, Esi Saari, Wolfgang
Birk, Khalid Atta

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Kammal Al-Kahwati^{1,†}, Esi Saari³, Wolfgang Birk^{1,2}, and Khalid Atta²

Abstract—Predictive maintenance strategies for the mining sector are of utmost importance considering the automated behavior of industrial systems and the oftentimes inaccessible environment around belt conveyor systems. In this paper, we present a model combining IoT sensors and dead-reckoning modeling, focused on early theoretical work in the field of modeling the behavior of belt conveyor systems to act as a decision support tool in maintenance strategies, by estimating the remaining useful life (RUL) of rotating components in a belt conveyor system. The estimation of RUL is a function of the degradation of the ball bearings in idler rollers due to the forces acting on the rollers during the conveyance of material. The forces occur due to the material loading, the belt weight, roller shell weight, and the idler misalignment load (IML). Furthermore, the dynamics of bulk material during conveyance can be modeled in several ways considering earth pressure theory. A model considering this is derived from the Krausse Hettler method to determine the forces acting on the wing rollers of a three-roll idler trough set by the notion that the bulk material undergoes active and passive stress states during conveyance. The model is further compared and extended to the works of Sokolovski, to get a bounded delta RUL reduction estimate on the roller bearings in each idler set of a belt conveyor system.

I. INTRODUCTION

Belt conveyors are widely used to continuously transport bulk material over distances ranging from some meters to tens of kilometers. Conveyor belt systems are employed in a vast amount of industries, including mining, automotive, and food processing to name a few. Compared to other types of bulk haulage modes such as railway or lorries, conveyor belt systems, especially when compared to the latter, present several advantages, such as: higher capacity, less human involvement, and reduction of business costs. Depending on the haulage load, belt conveyor systems can reduce costs by up to 40-60% concerning truck transportation[1].

In the process industry, belt conveyor systems are used to connect unit processes with each other by transporting refined bulk material from one unit process to the next and they are usually essential in a production chain requiring a high level of reliability. Adding buffers or storage after conveyors and at the inlet to the next unit process is a typical approach to increase the reliability of the production chain with the drawback of reducing flexibility and efficiency.

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¹ Predge AB, Västra Varvsgatan 11, SE-972 36 Luleå, Sweden.

² Control Engineering Group, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, SE-97187 Luleå, Sweden.

³ Strategic Maintenance Engineer, Luossavaara-Kiirunavaara AB, LKAB Kiruna, SE-981 86, Kiruna, Sweden.

[†] Corresponding author. E-mail: Kammal.Al-kahwati@predge.se.

Naturally, smaller buffers increase flexibility and efficiency but will require a more reliable operation of the conveyor with few short to no unplanned stops. Condition monitoring and predictive maintenance are therefore means to achieve this.

Belt conveyor systems have improved greatly since the second world war with increased rubber technology. In [2], Lodewijks describes how modeling of the dynamics began in the 1950s and can be split into three different periods from 1955 and onward. The first period (1955-1975) is characterized by the development of analytical solutions of the equations of motion of a belt, concluded with a discretized mathematical model. During the second period (1975-1995), finite element models capturing the time-dependent drive force, motion resistances, and the visco-elastic behavior of the bulk material were developed along with pioneering development in computer graphics for visualizations of simulation results from these models. The models developed during this era were to study the dynamic behavior of a belt in the longitudinal direction, which implies they were one-dimensional. Lodewijks further describes, the one-dimensional models only determine the longitudinal elastic response of the belt, falling short of accurately determining the motion and interaction of the belt over idlers and pulleys along with propagation of longitudinal stress waves and how it relates to the belt sag[2].

Nevertheless, condition monitoring is still in its infancy since monitoring of rollers with the aid of sensors due to the sheer number of rollers. The monitoring of larger components like drums, the belt, and drives is relatively well established [3] from the perspective sensing the condition of the equipment using e.g. vibration measurements [3], [4]. While it is an old idea to monitor the components using a model-based dead-reckoning approach [5] it has found its revival in the work by Lodewijks [2]. Combining these approaches with the modern IoT approach, therefore, presents an additional opportunity.

The contribution of this paper is the proposition of a condition monitoring and predictive maintenance approach which combines both IoT sensors and model-based dead-reckoning to determine the condition of rollers, their bearing, and drums. We propose a condition monitoring strategy for belt conveyor systems using real-time operational data of the plant to build a model calculating the forces exerted on each idler roller by the belt and its corresponding bulk load for a specific asset in the mining industry. Furthermore, the model calculates the remaining useful life (RUL) reduction and speed of the degradation of each bearing in the idler rollers to give a health status, as well as an indication of “hot spots” for

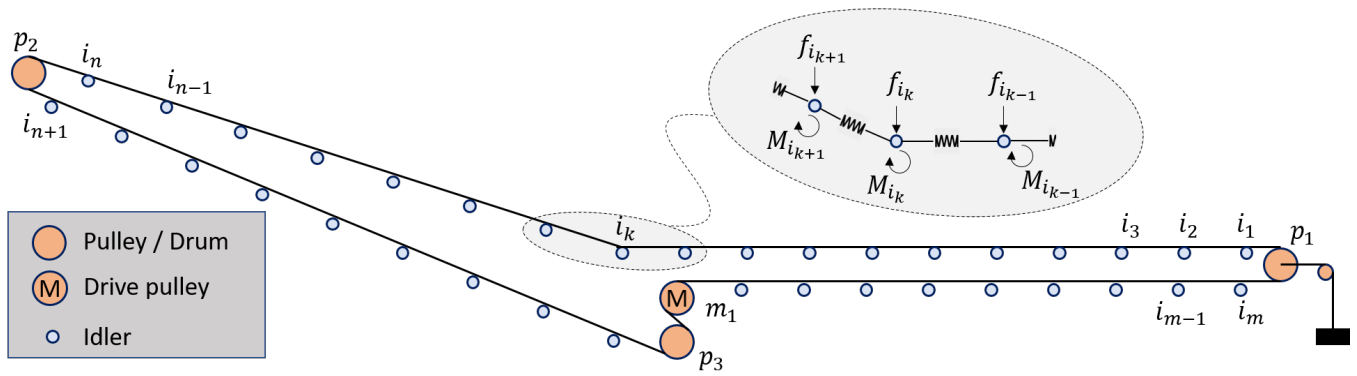


Fig. 1. Side view of a belt conveyor system.

prioritization of manual inspection. The proposed approach is realized as a software as a Service (SaaS) solution that can be easily integrated with any data sources surrounding a belt conveyor system. The solution is validated on a belt conveyor in operation in LKAB, Narvik, Northern Norway.

The paper is organized as follows. After the introduction, the belt conveyor system and its maintenance is explained, followed by the root cause analysis for stops in operation due to component failures. Thereafter the methodology for the condition monitoring is presented and then applied to a belt conveyor system case in a pilot project in LKAB, Narvik, Northern Norway. The results are discussed and some conclusions are given.

II. CONVEYOR BELT SYSTEMS

A principle sketch of a belt conveyor system is given in Fig. 1 indicating the different components. The primary component of a belt conveyor is the belt itself with the function to disseminate the necessary force for moving the load as well as to contain the material being transported. The belt surfaces on a series of idlers consisting of some rollers, often arranged as a set of three in a U-shape, see Fig. 2, but not limited to that. The belt wraps around a pulley on each end of the conveyor and is supported by several rollers on the return side. In addition, the drive mechanisms usually consists of a motor (hydraulic or electrical) providing the needed torque to drive the belt and pulleys to guide the belt around the drive drums. Clearly, the condition of the rollers, drums, pulleys and belt are affecting the operation of the CBS.

While industries are scaling up and finding more effective means for production by the aid of digitalization, the monitoring and diagnostics of the underlying processes are not keeping up. Rotating machinery, in general, is prone to faults and failures and in-production stops are very costly (well beyond €200K per hour in the mining industry) and need to be avoided. Unplanned downtime in a belt conveyor system generally occurs due to failures in the rotating components. Failures in the drive unit usually occur due to bearing failures either in the gearbox or the drive pulley. Breakdowns due to tail pulleys are attributed to bearing failures and roller failures are either due to bearing faults or damages in the outer

shell such as distortion and tears due to band slippage. Belt conveyor systems in the mining and haulage sector suffer from a higher affinity of breakdowns due to excessive loading and dusty environments. Furthermore, condition monitoring in these sectors is lagging behind other branches such as the energy sector, probably due to these harsh environments and dissipation of assets[6].

Usually, companies employing belt conveyor systems take necessary maintenance actions based on manual inspections to ensure reliability and high availability of the system. Under a preventive maintenance strategy, a set time or number of cycles interval is decided upon and the condition of the rotating parts are then evaluated by an expert in the field. They carry out the inspections mainly through visual or acoustic means, namely, looking and listening for issues [3]. Typical inspection routines performed in this way are considering almost all parts in an asset, such as idler rollers(outer shell and visible bearings), drive and tail pulley, output shaft, and hinge pin. Advantages of using such a practice are flexibility and low infrastructure investments, the inspectors can also easily adjust their routine if problems would frequently arise in a specific location of the asset, so called hot spot.

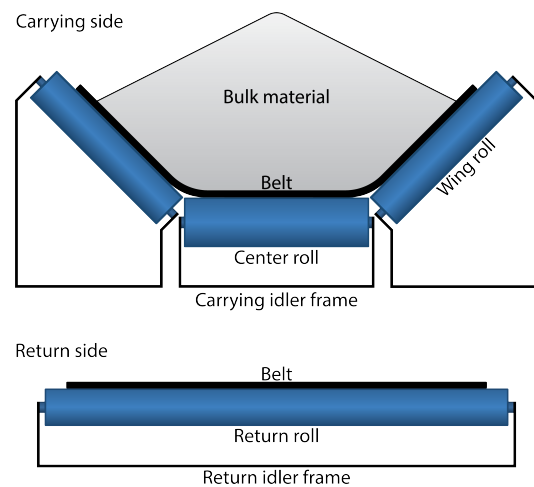


Fig. 2. Front view of a belt conveyor system.

However, it must be noted that this practice heavily relies on the people carrying out the inspections, and interpretations of the results vary depending on the experience of the personnel. The length of the inspection interval is decided based on previous experience and suggestions given in the data sheet or specifications from the supplier [7]. In the latter it may be difficult to monitor the remaining useful life of components in an asset using current maintenance strategies for logistical reasons. Furthermore, manual inspections of belt conveyor systems focus mainly on the end drum, drive pulley, and transfer stations. Since the rollers in a normal conveyor belt system deployed for haulage in the mining sector could be in the thousands, many of which inaccessible without special equipment, performing the manual inspection is virtually impossible.

Equipping the belt conveyor system with sensors is also a deployed practice. The gearbox and electrical motors in a belt conveyor system have since the 90's been equipped with temperature sensors, both inside the motor windings and on outside cases of bearings to protect them from overheating. Vibration and frequency analysis of accelerometer data is considered a more sophisticated tool, and an employed strategy also used on drive and end drums.

Belt rips can be avoided by installing magnets to divert scrap metal from the belt. Another strategy is to mold copper wire loops into the belt. The loop gets a current at one end and is measured on another to see if there exists a closed current loop [8]. Sensor-equipped idler rollers are not common in the industry due to relatively low costs for rollers and low consequence levels of a failure compared to other components in a belt conveyor system. However, considering the consequences of broken rollers onto other component such as belt degeneration and even tears, uneven loading which could propagate to other rollers to name a few, condition monitoring of idler rollers can be considered an important task.

Adding to this, visual inspection of idler rollers is not always feasible due to inaccessibility, and mounting sensors on thousands of bearings in hopes of predicting the asset's health from collecting vibration data is not feasible with today's standards. Mining companies deploy sensor systems on critical pulleys and would benefit from this information in combination with an estimate of the remaining useful life (RUL) for each roller in an asset, to gain insights on the overall health status.

III. ROOT CAUSE ANALYSIS FOR STOPS

The faults that may appear in the belt conveyor system have been grouped under three (3) categories namely fixed component failure, belt failure, and unwanted objects on the belt. This categorization is based on the stop events as shown in Fig. 3.

Each of the events identified leads to a stop of the belt conveyor system which in turn leads to a loss in production and consequently a loss in profit[9]. The level of risk that the stop events present is measured by the consequence level, or severity depending on the root cause and how much time

TABLE I
SIMPLIFIED ASSESSMENT OF FIXED COMPONENT FAILURES

Failures	Occurrence	Consequence	Priority
	(1=rare, 2= medium, 3=often)	(1=low, 3=high)	(1=highest)
Pulley Bearing	1	3	2
Pulley Lining/rubber	1	3	2
Pulley other	1	2	4
Roller bearing	3	1	1
Roller other/shell	3	1	1
Motor bearing	1	3	4
Motor other	1	3	4
Wrong tension	1	3	2
Output shaft	1	3	5
Hinge pin	1	3	5
Feeder	1	3	6

TABLE II
SIMPLIFIED ASSESSMENT OF BELT FAILURES

Failures	Occurrence	Consequence	Priority
	(1=rare, 2= medium, 3=often)	(1=low, 3=high)	(1=highest)
Misalignment	1	2	2
Rips and holes in belt	1	3	3
Steel cords wear	1	3	3
Hot material	1	3	6

and effort is needed to restore the functionality of the belt conveyor as well as the cost for restoring the functionality and the occurrence rate of the failure. Thus, in Table I, Table II, and Table III, we present a simplified assessment of the failures in the belt conveyor system based on the factors mentioned above.

As can be seen from Table I, Table II, and Table III, Priority 1 failures have the highest priority. Thus they need to be monitored in order to catch abnormalities early and to prevent unwanted stops and breaks in production as their occurrence can be devastating to the belt conveyor system and to production [9]. Priority 2 to 6 follow in ascending order with 6 being the least important. Other large objects that are hard are more hazardous to the belt conveyor system.

Further on, Table IV, Table V show the current fault detection method in the categories shown in Fig. 3.

TABLE III
SIMPLIFIED ASSESSMENT OF UNWANTED OBJECTS ON BELT

Failures	Occurrence	Consequence	Priority
	(1=rare, 2= medium, 3=often)	(1=low, 3=high)	(1=highest)
Unclassified	1	3	1
Loose wear plates	1	3	3
Detached lining (Silos)	1	3	3
Detached lining (Other)	1	3	3
Slabs of concrete	1	3	3
Big lump of frozen product	1	3	3
Personal belongings	1	3	3
Tools from workers on site	1	3	3
Other large objects	1	3	2

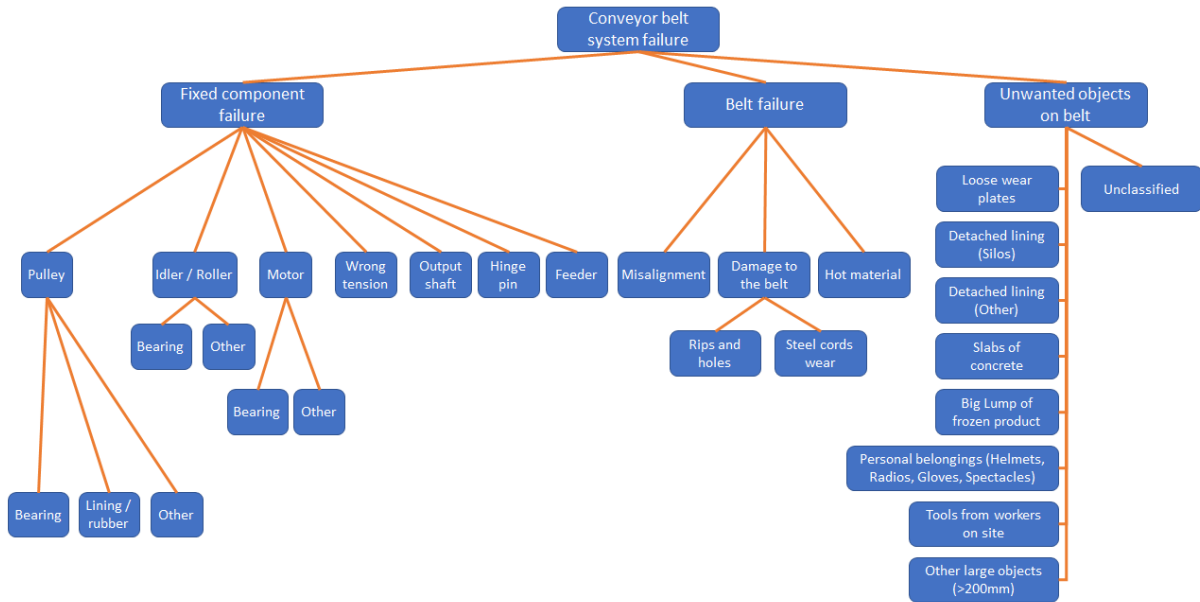


Fig. 3. Stopping event tree

TABLE IV
FIXED COMPONENT FAILURE DETECTION METHOD

Failure	Detection method
Pulley Bearing	SKF system on critical pulleys and visual checks
Pulley Lining/rubber	Visual condition monitoring control
Pulley other	Misalignment, tension pulley
Roller bearing	Visual condition monitoring control
Roller other/shell	Visual condition monitoring control
Motor bearing	SKF system on critical motors bearings and visual checks
Motor other	Electrical failure in circuit in motor
Wrong tension	Sensor for hydraulic, belt slip sensor and visual checks otherwise
Output shaft	Visual condition monitoring control
Hinge pin	Visual condition monitoring control
Feeder	Visual condition monitoring control

TABLE V
BELT FAILURE DETECTION METHOD

Failure	Detection method
Misalignment	Sensors on conveyor frame and visual checks
Rips and holes in belt	Critical conveyors have a Roxon detection system and visual checks
Steel cords wear	Magnetic X-ray system control and visual checks
Hot material	Not relevant for this paper

IV. METHODOLOGY

We present our framework for calculating the RUL on each roller in an asset by describing the underlying equations that form the model. Fig. 4 shows a simplified view of the CM solution architecture. Data from the real-time operation is fed to the model and the output of the model is the RUL of each component in the belt conveyor system.

The main objective of the model is to determine the forces that act on each ball bearing in the rollers of an idler set since these make up the main factor that will decide its deterioration, in addition to the rotational speed and the cleanliness of the lubrication used.

The belt is discretized into segments per idler distance. The segments have features such as distance to feed, loading, belt mass, tension, and elasticity. Feeding of bulk material,

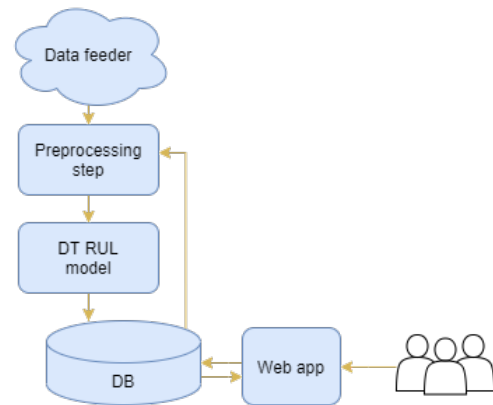


Fig. 4. Solution architecture

together with the geometry of the belt decides the loading and belt tension properties. Belt loading and material proliferation are calculated to find the height of the material and its distribution on the wing rollers. The forces acting on the rollers are then to be found. These occur due to the material loading, the belt weight, roller shell weight, and the idler misalignment load (IML). The frictional force between the bulk material particles and the belt is taken into

account independently in the different models used below. Adding with this, one must take the dynamic behavior of bulk material during conveyance into account. For this, there are several models developed, and we will take two of them into account.

The mathematical derivations of the dynamic behavior of conveyed bulk material and the forces presented to the idler rolls are based on the theory of Krause and Hettler[5], and Sokolovski's stress discontinuity method.

A. KH model

Krause and Hettler developed a method to determine the forces acting on the wing rollers of a three-roll idler set. The method is based on a modified version of Colomb's earth pressure theory and provides an analysis of the forces during active and passive stress states within the bulk material during conveyance. The active stress state is called as such during the opening of the belt, which Krause and Hettler assume is during the first half of the idler spacing, while the passive stress state occurs during the closing of the belt - during the second half of the idler spacing. The method further assumes that the bulk material is cohesionless and follows the theoretical shape as described in the standard DIN 22101[10].

The active pressure factor is described as:

$$K_a = \left[\frac{\sin(\beta + \phi_i) / \sin \beta}{\sqrt{\sin(\beta - \phi_w) + \sqrt{\frac{\sin(\phi_i + \phi_w) \sin(\phi_i - \lambda)}{\sin(\beta + \lambda)}}}} \right]^2 \quad (1)$$

and the passive pressure factor:

$$K_p = \left[\frac{\sin(\beta - \phi_i) / \sin \beta}{\sqrt{\sin(\beta + \phi_w) - \sqrt{\frac{\sin(\phi_i + \phi_w) \sin(\phi_i + \lambda)}{\sin(\beta + \lambda)}}}} \right]^2 \quad (2)$$

Where ϕ_i is the shear strength angle of the bulk material, ϕ_w is the friction angle between the bulk material and the belt, and β is the surcharge angle of the idler. Substituting the depth of the bulk material with $L_1 \sin \alpha$, Krause and Hettler applied the following equation to calculate the normal force on the wing belt during active stress state:

$$\frac{1}{4} \rho l g L_1^2 K_a \cos \phi_w \quad (3)$$

Where L_1 is the length of the bulk material on the wing belt. And for the passive stress state:

$$\frac{1}{4} \rho l g L_1^2 K_p \cos \phi_w \quad (4)$$

The model notes that by comparison of the cross-sectional area of the bulk load resting on an idler set, and between an idler set - a belt sag can be noted which acts as further stress on the idler rolls. The sag can be calculated as [4]:

$$l_{sag} = \frac{m_{bulk} + m_{belt} g l^2}{8T} \quad (5)$$

And the radial force on each idler as[4]:

$$F_{NG} = \frac{m_{bulk} + m_{belt} g l}{2 \cos \frac{g l (m_{bulk} + m_{belt})}{2T}} \quad (6)$$

B. SD model

In the SD model, presented by [4], Liu presents Sokolovski's stress discontinuity method to get a lower bound earth pressure theory solution as compared to the KH model which provides an upper bound. The same assumptions regarding the bulk material are made in this model, namely that the material is cohesionless and follows the theoretical shape as described in the standard DIN 22101[10]. Liu states that during experiments carried out on conveyed material, the sand on top of the cross-section slides down to the edge of the belt immediately after passing over an idler. This phenomenon can not be described by the hypothesis provided by Krause and Hettler.

Ilic [11] presents a hypothesis of a pivoting of the wing belt sections about the outer edges of the belt, and it is considered that the passive stress state is initiated by the upward pivoting (closing) of the wing belt, due to the tension and stiffness[4]. This is very logical considering the belt sags in between the idler sets. The normal and axial forces are calculated[4]:

$$F_{NG,w} = F_{NG,bulk,a} + F_{NG,bulk,p} \quad (7)$$

$$F_{NA,w} = F_{NA,bulk,a} + F_{NA,bulk,p} \quad (8)$$

Which leaves the forces acting on the center roll[4]:

$$F_{NG,c} = m_{bulk} g l - 2F_{NG,w} \cos(\alpha) - 2F_{NA,w} \sin(\alpha) \quad (9)$$

C. Relation - forces and RUL

The degradation of the ball bearings can be given by the following differential equation:

$$\dot{x}_{RUL} = \frac{L_{10}}{a_{SKF6} * 10^7 C^p} n F_B^p \quad (10)$$

Where L_{10} is the bearing life rating, a_{SKF} a factor of cleanliness, C is a bearing dynamic load rating, F_B the equivalent dynamic bearing load, which is a hypothetical load that when applied would have the same effect on the bearing rating life as the actual loads subjected on the bearing. The dynamic bearing load is calculated from the radial, -and axial forces multiplied with the radial, -and axial load factors for the bearing. For the case that the quotient $\frac{F_{NA}}{F_{NG}}$ is greater than the specified limit for the load ratio (specific table for each bearing can be found at the bearing provider). Should the quotient be below this limit, then the axial force is considered negligible and $F_B = F_{NG}$ [12]. Lastly the factor p is the exponent of the life equation [$p = 3$] for the bearing.

V. CASE STUDY

A. Description

We apply our methodology of calculating the forces exerted on each roller bearing. Table VI describes the real-time data collected at the asset site. The digital twin of the asset is fed with the data but may also be inspection, maintenance data, and third-party condition data.

TABLE VI
DATA POINTS RECEIVED FROM THE ASSET SITE.

Data point	Description	Source
Working pressure	Working pressure of piston[bar]	DCS
Conveyor Speed	Belt speed[% of 3m/s]	DCS
Scale	Mass of bulk material[tonnes/h]	DCS

The asset in question is a three-roll idler trough set belt conveyor system, located in LKAB, Narvik, Norway. Expected operating conditions for the belt conveyor system are a conveying speed of 3 m/s, belt tension of 155kN (take-up), and a bulk tonnage loading of 9000 t/h. This results in a bulk mass loading of roughly 833 kg/m. Since the RUL of the components was not known beforehand, the components of the digital twin are initialized at 50% health.

Raw data from the belt conveyor is captured upon change within a set threshold. When there is an update, the data is pushed to a stream. On the receiving end, the data is backed up and then sent to a queue. Messages are then received from the queue upon request to process, and the dataset is preprocessed in a first step to create features useful for the model interpretation. The new features correspond to the columns in Table VII, and each row corresponds to a message. Since the messages are tagged with the timestamp of the measurements, the extended feature set can be very precise, with the actual speed[m/s], bulk load[kg/m], time since last measurement[s, d_time], length traveled since last measurement[m, d_len].

The measurements are then traversed through the conveyor belt of the digital twin in an iterative manner, and forces acting on all bearings in an idler set are computed using the models proposed, and subsequently, the RUL reduction is calculated and reduced from the total expected life of the bearing, which is a provided specific from the bearing supplier. Results are presented using the SD model and the KH model.

TABLE VII
EXTENDED FEATURE SET FROM THE DATA POINTS RECEIVED.

timestamp	speed	scale	tension	m/s	bulk	d_time	d_len
03:37:40	84.3	5250	155	2.53	576	30.0	75.9
03:38:10	82.6	5250	155	2.48	588	30.0	74.4
03:38:40	82.6	5315	155	2.48	595	30.0	74.4

B. Results, KH model

In the other scenario conducted, the same loading conditions as in section V-C were applied to a model using the underlying equations developed by Krausse and Hettler [5]. The model is based on Müller-Breslau's principle used to determine influence lines, regarding the belt sag during conveyance of material on a belt conveyor. When comparing the cross-section of the bulk load that sits on top of an idler with the bulk load in the middle of two idler sets, a belt sag can be noticed. The resulting force can be compared to that of a line hanging through a trundle. Thus the rollers can be seen as the trundle and the belt as the line. For these

calculations made, the model assumes that the belt opening occurs in the first half of the idler spacing and the closing in the second half. The model assumes that the bulk material is homogeneous and cohesionless and that the cross-section of the bulk material follows the standard DIN 22101 [10].

Fig. 5 present the resulting RUL reduction for the center and wing roll bearings (inner and outer) respectively.

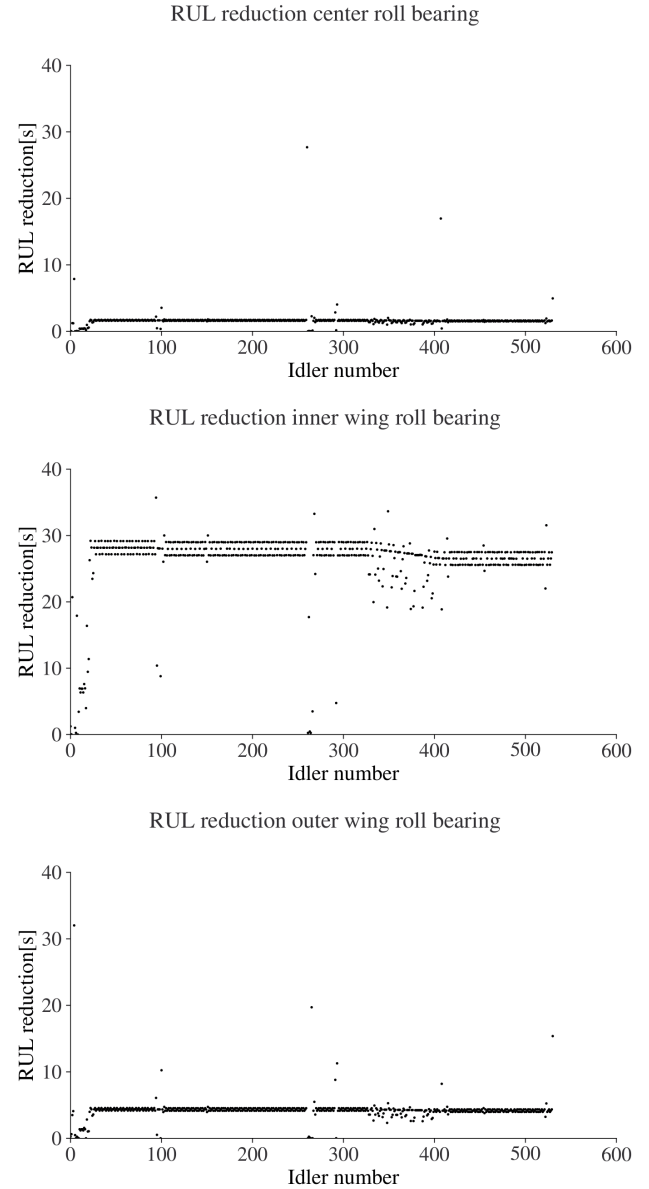


Fig. 5. Scatter plots of the RUL reduction for center roll bearings, inner wing roll bearings, outer wing roll bearings using the KH model.

C. Results, SD model

The SD model assumes that the bulk material is homogeneous and cohesionless and that the cross-section of the bulk material follows the standard DIN 22101 [10]. A message consisting of the data found in the first row of Table VII is traversed through the model. The bulk mass was calculated to be 576 kg/m which corresponds to a loading level of

69% which is typical for the belt conveyor in question. The speed of the belt was traveled with a start speed of 2.53m/s. Fig. 6 present the resulting RUL reduction for the center roll bearings, inner wing roll bearing, and outer wing roll bearings respectively for these loading, belt tension, and conveyor speed conditions.

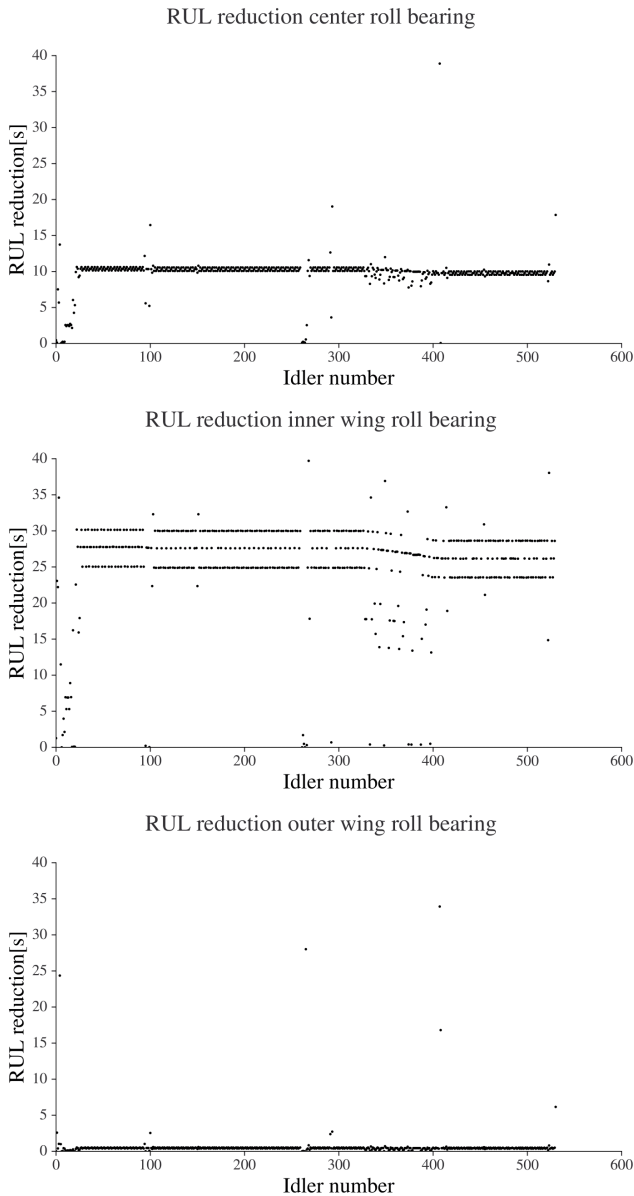


Fig. 6. Scatter plots of the RUL reduction for center roll bearings, inner wing roll bearings, outer wing roll bearings using the SD model.

VI. DISCUSSION AND CONCLUSIONS

This paper presented a decision support tool for condition monitoring of belt conveyor systems by calculating the RUL and the delta RUL for components. The methodology is based on the theoretical work done by Krause and Hettler[5], X.Liu[4], and further extended to the method described in section IV-C.

It is shown how stop events in the maintenance logs can be mapped to different root causes, that in turn motivate a prioritization for the condition monitoring strategy. As a result, rollers were chosen as the primary component for the condition monitoring. Using the theoretical framework a digital twin for the belt conveyor system is setup and run in parallel with the live operating system, enabling the solution to track the current stress conditions for the each roller over time.

One can note in Fig. 6 and Fig. 5 that the results obtained from the different models behave slightly differently, with the KH model estimating a higher degradation rate of the outer wing roller than the SD model. On the contrary, the inverse relationship is true for the degradation rate of the center roller, namely that the SD model estimates a higher degradation rate regarding this roller. At the time of writing the validation of the models is ongoing where the digital twin is tracking all rollers in the system and determining RUL and the degradation rates.

Due to the difference in the degradation rates, potential over and underestimation, an aggregate model should be investigated for the estimation of the degradation rates and validated for the same operating conditions during the current validation.

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