System reliability analysis of belt conveyor

by

Bart Zeeuw van der Laan

Supervised by: Dr. ir. X. Jiang
Transportation Engineering

March 2016
This report is about the reliability of Belt Conveyor Systems. A literature search has been conducted, about the working principles of sub-systems and components from the belt conveyor system. Some general information about reliability is given. Later a feasible state-of-the-art solution for improving the design of the belt conveyor system in order to increase the overall reliability of the system.
As an important transportation equipment, belt conveyor has been widely applied in mining yards, harbor and airport etc. Typically, a belt conveyor consists of large numbers of components and subsystems; Moreover, the status of those components and subsystems would change with time and operation process. The complexity of both system and operation processes of a belt conveyor makes it very complicated and thus difficult to evaluate the safety and the reliability of a belt conveyor. In those regards, it is essential to introduce system reliability method to the design, evaluation and optimization of a belt conveyor in order to maintain its safety and operating process effectiveness.

In this literature assignment, the student is demanded to review the development of system reliability method and its application on the design, evaluation, maintenance and optimization of belt conveyors. The following aspects are required to be illustrated in the report:

- Explain the basic theory of system reliability and available approaches/methods.
- Identify the main components and subsystem of belt conveyer, their failure modes and inter-relationship between those failure modes (dependent or independent; in series, or parallel or others).
- Identify the main operation processes and their distribution in time domain; the status of components and subsystem with related to each operation process.
- Illustrate the state of the art: application of system reliability to design, evaluate, inspect and optimize belt conveyors.

This report should be arranged in such a way that all data is structurally presented in graphs, tables, and lists with belonging descriptions and explanations in text.

The report should comply with the guidelines of the section. Details can be found on the website. If you would like to know more about the assignment, you may contact with Dr. X Jiang through x.jiang@tudelft.nl.

The supervisor,

X Jiang
## Contents

**Abstract** iii

**Assignment** v

1 **Introduction** 1

2 **General reliability** 3

   2.1 General reliability ....................................... 3
       Failure .......................................................... 4
       Two state failure mode ..................................... 4

   2.2 Failure rate .................................................. 4
       Chance of failure ............................................. 4
       Cumulative failure distribution: ......................... 4
       Survival rate: the probability that an item works until time T
       Reliability function is the probability that the unit serves
       the time interval t ........................................... 5
       Failure rate: .................................................. 5

   2.3 Life cycle .................................................... 5
       2.3.1 Infant mortality phase ................................. 5
       2.3.2 Normal life ............................................. 6
       2.3.3 Wear out ................................................ 6
       2.3.4 Random overstress .................................... 6

   2.4 Multistate reliability ...................................... 6
       2.4.1 Failure rate data ....................................... 7
       2.4.2 Online and offline ..................................... 7

   2.5 Systems ...................................................... 7
       2.5.1 Reliability Block diagram ............................. 7
       2.5.2 Interrelationships ..................................... 8
       Series ............................................................. 8
       Parallel .......................................................... 8
       Combination of parallel and series ...................... 8

   2.6 Redundancy .................................................. 9

   2.7 FMEA .......................................................... 10
       2.7.1 FMEA Failure mode and effects analysis ............ 10
       2.7.2 Frequency/Consequence diagram .................... 10

   2.8 Failure and failure modes ............................... 10
# Components of Belt Conveyor Systems

## 3.1 Belt conveyor systems

## 3.2 Definition

## 3.3 The system

## 3.4 Components

## 3.5 Belt

### 3.5.1 Belt structure

### 3.5.2 Carcasses

### 3.5.3 Belt cover

## 3.6 Idlers

### 3.6.1 Idler structure

### 3.6.2 Types of idlers

### 3.6.3 Transition zone

## 3.7 Pulleys

### 3.7.1 Drive pulley

### 3.7.2 Drive pulley structure

## 3.8 The drive unit

### 3.8.1 Drive unit components

### 3.8.2 Subsystems drive unit

#### Motor

#### Coupling

#### Gearbox

#### Bearings

## 3.9 Take-up system

### 3.9.1 Transfer power

### 3.9.2 Take-up system structure

#### Types of take-up systems

### 3.9.3 Gravity take-up system

### 3.9.4 Winch take up system

### 3.9.5 Screw take up system

## 3.10 Brake

### 3.10.1 Brakes

---

# Belt conveyor failure modes

---
4.1 Schematic overview of the belt conveyor system .................................................. 31
  4.1.1 Sub-systems ....................................................................................................... 31
  4.1.2 The drive system ............................................................................................... 32
  4.1.3 The belt .............................................................................................................. 32
  4.1.4 The idlers .......................................................................................................... 34
  4.1.5 The take-up system ......................................................................................... 34
  4.1.6 Brake system ..................................................................................................... 35
4.2 Failure modes of belt conveyor system ................................................................. 35
  4.2.1 Complete system .............................................................................................. 36
  4.2.2 $S_1$ Belt .......................................................................................................... 37
  4.2.3 $S_2$ Drive system ........................................................................................... 38
  4.2.4 Failure mode of the idler system ...................................................................... 38
  4.2.5 Failure mode of take up system ....................................................................... 39
  4.2.6 Failure mode of brake system ........................................................................ 39
5 Operation modes ........................................................................................................ 41
  5.1 Process states ....................................................................................................... 41
  5.2 Belt conveyor operation states ............................................................................ 41
  5.3 Time distribution operational processes ............................................................... 42
      Normal operation .................................................................................................. 42
      States .................................................................................................................... 42
  5.3.1 Steady state running $z_1$ ................................................................................ 43
  5.3.2 Normal operational start $z_2$ .......................................................................... 43
  5.3.3 Normal operational stop $z_4$ ........................................................................... 43
  5.3.4 Emergency stop $z_5$ and Aborted start $z_3$ .................................................. 44
  5.3.5 System at rest $z_6$ .......................................................................................... 44
  5.4 Fuzzy logic with Bayesian .................................................................................... 44
6 Automated reliability optimization ............................................................................ 49
  6.1 Conveyor belt system monitoring ........................................................................ 50
      6.1.1 Automated belt conveyor monitoring ......................................................... 50
      6.1.2 Belt monitoring .............................................................................................. 51
      Belt interior monitoring ....................................................................................... 52
      Belt surface monitoring ...................................................................................... 52
      Speed monitoring ................................................................................................ 52
      6.1.3 Force tension and torque measurement ...................................................... 53
      6.1.4 Vibration monitoring ................................................................................... 54
      6.1.5 Power monitoring ....................................................................................... 54
      6.1.6 Misalignment monitoring ............................................................................ 55
      6.1.7 Temperature monitoring ............................................................................. 55
  6.2 Decision making .................................................................................................... 55
      6.2.1 Artificial intelligence .................................................................................... 57
      6.2.2 Assessment for intelligent monitoring system ............................................. 57
  6.3 Reliability optimization ......................................................................................... 57
7 Conclusion .................................................................................................................. 59
  7.1 Recommendations ................................................................................................. 60
Chapter 1

Introduction

Belt conveyor systems are used worldwide for multiple different options. They have been around for about 250 years. Lodewijks [2014] Belt conveyor systems are in use and have been used, for transporting people, bulk cargo and general cargo.

Belt conveyor systems are relatively complex systems used in heavy industry. They contain of many rotating parts subject to wear. As in every industry the reliability of systems is an important factor in the complete operation. Compared to other sectors however relatively not that much reliability optimization has been done relating to the operation and design of the system.

In sectors like the aircraft industry and offshore engineering a lot more research has been done and the implantation of reliability centered maintenance is a lot further. By using automated monitoring and decision systems predictive maintenance can be scheduled instead of running the system until a random failure occurs.

In this report general reliability will be explained (Chapter 2) and the system of the belt conveyor will be studied (Chapter 3). The different failure modes of the sub-systems and components will be shown (Chapter 4) and the operation states are determined (Chapter 5). Later possible modern options for the improvement of reliability of belt conveyors will be shown (Chapter 6).
Figure 1.1: A belt conveyer system
Chapter 2

General reliability

Over the years systems being used by mankind in all sectors of our society have become more and more complex. By getting more and more complex these systems have become a lot more advanced, but a good understanding of the reliability of the system has become a lot harder. By the growing number of components and sub-system the cumulative chance of one of these failing increased. Failing of one of these components or sub-systems may cause the total system to fail. The total reliability became more and more important. In order to get a better understanding for this, reliability engineering is used. In the following section general reliability and failure are explained.

A system usually is a set of multiple subsystems. These sub-systems then can be made up out of multiple different components. Failing of one of these components, may affect, or lead to failure of the working of the entire system. Due to demands for cheaper safer and highly reliable systems, for use in multiple different areas of work, two different techniques for achieving high system reliability have been identified. Simply increasing the strength or increasing the amount of backup solutions. The other technique for improving the system reliability is a component reliability improvement program

2.1 General reliability

Reliability is about whether a system, sub-system or component will not fail. According to accepted standards 1 failure is defined as 'the termination of the ability of an item to perform a required function.'
Failure  In general reliability theory a system, subsystem or component is either working or not working. A component works until the moment it fails. This is usually a function of time, but also other variables are possible.

Two state failure mode

\[ X(t) = \begin{cases} 
1 & \text{component is working at time } t \\
0 & \text{component is not working at time } t 
\end{cases} \quad (2.1) \]

Failure modes According to British Standard BS 5760, Part 5, 3 failure mode is defined as 'the effect by which a failure is observed on a failed item'.

2.2 Failure rate

The failure rate is the frequency with which an engineered system or component fails, expressed in failures per unit of time. The failure rate of a system usually depends on time, the rate varies over the life cycle of the component or system. In most cases the failure rate is expressed in hours of use. Other possible options are to use distance or revolutions etc. these can than replace the value of time. The failure rate is denoted by \( \lambda \). [Rausand, 1998]

Chance of failure  \( f(t) \) is the chance a component fails on a certain time

Cumulative failure distribution:

\[ F(t) = \int_0^t f(t) \, dt \quad (2.2) \]

\[ F(t) = 1 - R(t) \quad (2.3) \]

\[ R(t) = 1 - F(t) \quad (2.4) \]

Survival rate: the probability that an item works until time \( T \)

\[ F(t) = 1 - e^{-\lambda t} \quad (2.5) \]
Reliability function is the probability that the unit serves the time interval $t$

$$R(t) = e^{-\lambda t} \quad (2.6)$$

Failure rate:

$$r(t) = \frac{f(t)}{R(T)} \quad (2.7)$$

### 2.3 Life cycle

Most components have a similar life cycle curve. This curve showing the failure rate as a function of time, is sometimes referred to as the bathtub curve. The curve is named after its typical shape as a bathtub. The life cycle of most products have three typical phases; the infant mortality, the normal life and the wear-out phase. The failure rate decreases during the first phase, stays pretty much constant during the normal life phase and then increases in the wear out phase (see figure: 2.1).

![Bathtub Curve](image)

**Figure 2.1: Bathtub Curve**

#### 2.3.1 Infant mortality phase

During the infant mortality phase also known as the burn in phase the component is new and can suffer from manufacturing mistakes. For this reason the component has a high likelihood of failing during the beginning of their operating life. Small manufacturing mistakes not visible at first will be seen shortly after first use. The reason for failure
during this part of the operating process is mostly due to a mistake in manufacturing or installation.

2.3.2 Normal life

After the burn in phase all the components with manufacturing or installation mistakes are filtered out. The rate of failure usually then drops to a more constant lower level where it will stay during its normal operating life. The component of course wears, but is still able to fulfill its task. During this phase of the lifetime cycle there is still a chance the component will fail but its lower and at a pretty much constant rate.

2.3.3 Wear out

Over time the component start to wear out more and more. Finally causing it to wear out beyond proper use and or increasing the chance of direct failure. In this time of the cycle the failure rate increases exponentially.

2.3.4 Random overstress

Except for usually regularly occurring patterns as the braking in phase and the wear out; overstress is also an option of failure. During any time of the process its possible that the component is put under a overstress causing it to fail.

2.4 Multistate reliability

For more complex system who age over time and its possible to introduce a multistate analysis. [Yingkui and Jing, 2012] This allows to distinguish the overall reliability when one or more components are aging. The amount of states is denoted by z. In the example below z=3. [Rausand, 1998]

- a reliability state 3 the system operation is fully effective
- a reliability state 2 the system operation is less effective because of ageing
- a reliability state 1 the system operation is less effective because of ageing and more dangerous for the environment
- a reliability state 0 the system is destroyed
2.4.1 Failure rate data

In order to better predict the failure of a component its possible to gather data about a system or component. There are different ways of getting this data. The best and most accurate one is testing the actual devices in order to generate failure data. Often this is not completely possible and then instead historical data from similar systems is used.

2.4.2 Online and offline

To establish maintenance strategies and especially function testing strategies, it is important to distinguish between so-called evident and hidden failures. The following classification of functions may therefore prove necessary:

1. On-line functions: These are functions operated either continuously or so often that the user has current knowledge about their state. The termination of an on-line function is called an evident failure.

2. Off-line functions: These are functions that are used intermittently or so infrequently that their availability is not known by the user without some special check or test. An example of an off-line function is the essential function of an emergency shutdown system. Many of the protective functions are off-line functions. The termination of the ability to perform an off-line function is called a hidden failure.

[Rausand, 1998]

2.5 Systems

A system exists of multiple components working together. Therefore the working of the system is depending on the working of the components. Depending on how the system is build up failure of a certain component also lets the whole system fail or not. This depends on the structure of the components in the system.

2.5.1 Reliability Block diagram

To retain the understanding of the functional interactions in the functional hierarchy, and to clarify the required input and output interfaces, it is often useful to establish so-called functional block diagrams. A block diagram is a clear way of modeling a system.
A block diagram contains different blocks representing components or sub-systems of a bigger system. The blocks are connected by lines showing their relationship. For a system to work, there must be a working route along the blocks from start to the end. If one of the components fails, it’s not possible to walk the route going over that block anymore.

2.5.2 Interrelationships

In a system, components and subsystems can be in parallel or in series.

**Series** If the components of a system are in series, the whole system will fail if one of the components or sub-systems fails. To calculate the chance of a system not failing when components are placed in series, multiply their successive survival rates.

\[ R(t) = R_1(t) \times R_2(t) \times R_n(t) \]  

**Parallel** In a parallel configuration, at least one of the components in a parallel configuration need to work in order for the system to work. Parallel configuration quickly get a much better reliability since all of the components have to fail in order for the system to fail. To calculate the chances of a system in parallel for not failing is the same as the chance of all the separate components in series failing.

\[ F(t) = F_1(t) \times F_2(t) \times F_n(t) \]  

With formula 2.4, this can be translated to the reliability function again.

**Combination of parallel and series** It’s possible to make combination of parallel and in series schemes in order to simulate more complex systems. Like the system below which is a combination of parallel and in series components. This system already has multiple different options for working when one of the components fails.
2.6 Redundancy

In general criteria to be optimized can be system reliability, system cost, system weight, or system volume. System reliability can be increased by either using redundant components or using components of higher reliability. Redundancy is using multiple components, sub-systems or even complete systems in parallel to improve overall reliability. By putting two components, who can both do the job individually, in parallel the overall reliability increases. The complete system can now keep on working until both of them fail. With only one of them failing the whole system will be able to continue. [Li et al., 2009]

In general is often more economical to increase the number of redundant components than to improve component reliability because component cost may increase exponentially with increased reliability. [Misra and Ljubojevic, 1973]

In the case of belt conveyor system which are large and by design not possible to add redundant components and sub-systems everywhere, this solution is not really possible to use everywhere. The optimization is all about improving the reliability compared to
the added costs. If the gains don’t out way the benefits it isn’t feasible. So for the design of belt conveyors there is not so much to be gained using redundancy.

2.7 FMEA

2.7.1 FMEA Failure mode and effects analysis

The failure mode and effects analysis gives an overview of different components like-lihood to fail and the consequences this may have. FMEA usually starts during the early phases of system design and is performed by following the seven steps shown in 2.5. Some of the questions asked during the performance of FMEA with respect to components/subsystems are as follows:

- What are the possible failure modes of the component/subsystem?
- What are the possible consequences of the failure mode?
- How is failure detected?
- How critical are the consequences?
- What are the effective safeguards against the failure in question?

2.7.2 Frequency/Consequence diagram

In order to better understand and to give values to the frequency of different components and systems failing they are sometimes categorised in a frequency/consequence diagram. In this diagram all the different failure options are categorised by how likely they are to occur and what the pairing consequence will be. The failure options are ranked with a value from 1 to 5 for both the frequency as the severeness of the consequence. At this way its easier to compare the different components with each other. Depending on the type of the system the severeness of the consequences may vary and these need to be established in order to make a fair comparison.

2.8 Failure and failure modes

Even if we are able to identify all the required functions of an item, we may not be able to identify all the failure modes. This is because each function may have several failure modes. No formal procedure seems to exist that may be used to identify and classify the possible failure modes. Rausand and Øien [1996]
A failure mode is a manifestation of the failure as seen from the outside. This means the termination of one or more of its functions. Furthermore it’s important to make a good distinction between the cause of failure and the failure mode itself.

**Cause of failure**  Failure cause is ‘the circumstances during design, manufacture or use which have led to a failure. This is what eventually causes a failure like for example wear.
Failure modes can be classified in three main groups related to the function of the item:

1. Total loss of function: In this case a function is not achieved at all, or the quality of the function is far beyond what is considered acceptable.

2. Partial loss of function: This group may be very wide, and may range from the nuisance category almost to the total loss of function.

3. Erroneous function: This means that the item performs an action that was not intended, often the opposite of the intended action.

2.9 Markov Method

For any given system, a Markov model consists of a list of the possible states of that system, the possible transition paths between those states, and the rate parameters of those transitions. In reliability analysis the transitions usually consist of failures and repairs. When representing a Markov model graphically, each state is usually depicted as a bubble, with arrows denoting the transition paths between states, see figure 2.7 for a single component that has just two states: healthy and failed. [Bazzi et al., 2012]

The symbol λ denotes the rate parameter of the transition from State 0 to State 1. In addition, we denote by \( P_j(t) \) the probability of the system being in State \( j \) at time \( t \). If the device is known to be healthy at some initial time \( t = 0 \), the initial probabilities

<table>
<thead>
<tr>
<th>Index</th>
<th>Parameter</th>
<th>Frequency</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ext</td>
<td>Remote</td>
<td>Extremely Minor</td>
</tr>
<tr>
<td>2</td>
<td>Remote</td>
<td>Minor</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Frequent</td>
<td>Major</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Ext</td>
<td>Ext Major</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.6: Frequency/Consequence diagram
of the two states are $P_0(0) = 1$ and $P_1(0) = 0$. Thereafter the probability of State 0 decreases at the constant rate $\lambda$, which means that if the system is in State 0 at any given time, the probability of making the transition to State 1 during the next increment of time $dt$ is $\lambda \ast dt$.

$$dP_0 = -(P_0) \ast (\lambda \ast dt) \quad (2.10)$$

2.10 Fault tree method

Another widely used method is the Fault tree method. It uses different kind of blocks to show the types of linkages. Figure 2.8 shows the four most commonly used blocks in fault trees. [Dhillon, 1989] The Fault tree method, makes a better understanding of the system. With analyzing tools and optimization the reliability can than be improved.

The fault tree is structured using the following steps: see figure 2.9
2.11 Progressive reliability method

A progressive reliability method calculates the failure probability of a structural system accounting for the progressive failure of system components until the system fails. In this method, two important terminologies are essential and frequently referred to, which are (a) a configuration and (b) a failure scenario.

We define a configuration as any possible state of the structure in terms of the possible state (failure or no failure) of its components. This definition is based on the assumption that any component may fail and is always either in the state of failed or in the state of not failed. Any structural system has an initial arrangement of its components. We call the initial state of a structural system (with no failed components) as the intact configuration. Under the effect of environmental loads, some components may fail. Any component failure leads the system to a new configuration. If a system has N components that may potentially fail, the total number of possible configurations is $2^N$.

We define a failure scenario of $X_i$ as a group of steps (or the path) that leads the system from $X_0$ (the intact configuration) to $X_i$. In general, the occurrence of $X_i$ can be through one or more failure scenarios. However, because in a structural system, the environmental loads usually vary within a time frame until reaching to a maximum load, and that the capacity of the components are random, it is almost impossible that in more than one component, the internal force exceed the capacity at the same time. Therefore we assume that one component fails at a time. [Mousavi et al., 2013]
The method is best explained with an example of two beams being able to withstand a force when they work in pairs. When one of them breaks the other will follow since it won’t be able to withstand the force by itself.

2.12 Causal modeling theory

Causal modeling theories provide the user intuitive and mathematically sound tools to model complex relations between uncertain variables and failure causes. The development of causal modeling is resulting in the development of new diagnostic and decision-making methodologies in field of large-scale conveyor belt systems. Pang and Lodewijks [2006]

However, not all modeling methodologies can fully match the requirements of practical conveyor belt systems maintenance decision-making. The Bayesian method compared to the other methodologies has the advantage of handling both discrete and continuous events and reasoning with partial or limited information. [Pang and Lodewijks, 2006]

The Bayesian Belief Network method is explained in the next section.

2.13 Bayesian Belief Network

Bayesian Belief Networks are based on the Bayesian method. The method is a mean to calculate the likelihood of a future event based on the frequency the event has occurred in the past.

Bayes rule:

\[
P(A|B) = \frac{P(B|A) \times P(A)}{P(B)}
\]

\(P(A)\) is the prior probability of the likelihood of event A. The event A is considered as independent from other events and the probability doesn’t take into account information about other events. \(P(B)\) is the prior probability of the likelihood of event B. The event B is considered as independent from other events and the probability doesn’t take into account information about other events. \(P(B|A)\) is the probability that B occurs given that A occurs. It is the posterior probability of event A, which is derived from the specified value of event B. The rule shows the condition between two reverse probabilities.
Bayes rule allows to gain posterior knowledge by using prior knowledge to calculate the probabilities of other events. Bayesian interference is therefore used to see the cause effect relationships between evidence and hypothesis. [Langseth and Portinale, 2007]

The Bayesian method can be used in two ways. It can either be used forward and backward. In the forward interference the effects are derived from the causes. This will enable prediction of events. Knowing that components have worn out will lead to less well operation. With the backward interference the causes are derived from the effects. By observing poor operation it can be derived that components are wearing out.

The method can be used to determine the cause-effect relationship between evidence and hypothesis. The posterior probability \( P(E|H) \) of an event or evidence \((E)\) can be derived with the observed hypothesis \((H)\). This can be used to identify the cause of an event. This is called the backward interference. It can also be used the other way around \( P(H|E) \) to discover the effect of an event. This is called the forward Bayesian interference. [Langseth and Portinale, 2007]

The rule shows that the hypothesis is closer to the truth by means of the events that have been observed. Considering multiple events the rule expressed as:

\[
P(e_i|H) = \frac{P(H|e_i) \times P(e_i)}{\sum_i P(H|e_i) \times P(e_i)}
\] (2.12)

The prior knowledge \( P(e_i) \) of a set of events \( e_i(i = 1, 2, 3, ..., n) \) is used to find out the posterior knowledge of \( P(e_i) \) of the set of events given hypothesis \( H \).

A Bayesian Belief Network is a network with on the nodes the probabilistic functions and connecting the relationships. In automated networks new data is used to update all the possible events.

The belt conveyor system has a lot of components which can not be measured directly but the effects can be measured. By combining all the effects and using a Bayesian Belief Network new inside can be given about the state of components which otherwise would’ve been hard to notice.

2.14 Fuzzy logic

In order to transform the data measured to more quantified data to be used in automated systems. Fuzzy logic is used to transform the fuzzy data to be more easily used. [Zadeh, 1983]
According to [Lodewijks, 2014] there are five reasons to use fuzzy logic as a tool to use on the data for the conveyor belt system.

- It allows interpretations of more fuzzy observations
- It increases the consistency of the inspection if the observations are done by different interpreters.
- It allows to combine the inspection data to be combined with other source information.
- It allows objectification of the results
- It gives a straightforward advice

![Fuzzy example on temperature classification](image)

**Figure 2.10: Fuzzy example on temperature classification**

Fuzzy logic are a way to quantify measurements into data which is more easily used. The basics of fuzzy logic can be described by the function:

$$A : X \rightarrow [0, 1]$$ (2.13)

The fuzzy set $A$ is characterized in a non-empty set $X$. The degree of membership by an element $x$ is $A(x)$ for each $x \in X$. Where 1 is complete membership and 1 is completely not. Values in between are for intermediate memberships. As can be seen in figure 2.10, once the temperature increases from cold to warm there is a state where the temperature is quantified to be half cold half warm. In the conveyor belt system this technique can be used to quantify all sorts of states of components. For example; abrasion of surfaces, cracks in the conveyor belt, the power of the motor, the state of the rollers, etc.

It is feasible to use Fuzzy logic in conveyor belt systems as shwon by [Mazurkiewicz, 2015]
2.15 Historical data

In order to have the reliability values of components real data of the working components gives the best values. In order not having to test every single component over a complete lifespan a database could be used. This kind of databases have proven to be a well working extra in comparing the values measured from a system and making better decisions. In the offshore sector OREDA has been a proven example of a system which has been in use trough multiple offshore operators. Rausand [1998] The OREDA database covers a very large amount of components used in systems by different offshore operators. The data allows other companies to gain knowledge about the failure rates and lifetime expectancies of components. Especially for the components who have longer lifetime and where testing would be a very costly exercise, this gathered information from the same component also used in the field could be very beneficial.
Chapter 3

Components of Belt Conveyor Systems

Belt conveyors systems are commonly used systems for continuous transport, they have a high efficiency, large conveying capacity, relatively simple construction and relatively small amount of maintenance. In the next part the different components and subsystems of the belt conveyor system will be explained. From these different systems and subsystems the failure modes and interrelationships between these failure modes will be explained.

3.1 Belt conveyor systems

Belt conveyor systems are used worldwide for multiple different options. They have been around for about 250 years. Lodewijks [2014] Belt conveyor systems are in use and have been used, for transporting people, bulk cargo and general cargo. In this report the focus will be on belt conveyors for bulk cargo. These belt conveyor systems play an important role in the mining industry, bulk terminals, power plants, and chemical production. Belt conveyor systems can be used in places where the terrain is rough and where there is no current infrastructure of roads or railroads. Belt conveyor systems will then be a highly efficient way of continuously moving bulk material fast. Fedorko et al. [2013]
3.2 Definition

A belt conveyor is a continuous conveyor that consists of two or more pulleys, with a continuous loop of material - the conveyor belt - that rotates about them. At least one of the pulleys is powered, moving the belt and the load on the belt forward.

3.3 The system

The belt conveyor system consists of different components. The major components are: the belt, pulleys, idlers, take-up system, drive unit and sometimes the brakes. A belt conveyor system is always being used in a bigger system. For this report the focus is on the belt conveyor itself therefore leaving out the different parts of the complete system. For example the loading hopper is not being taken into account in this report. The different systems containing of subsystems which will be shown later in the report.

![Figure 3.1: A Belt Conveyor System](image)

3.4 Components

3.5 Belt

The belt is the major component of a belt conveyor system. It is constantly moving around with the transporting good on top. The bulk material should have a relative speed of zero compared to the belt itself.
3.5.1 Belt structure

The belt consists of two main components: its carcass and belt covers. The carcass of the belt is to transfer the power of the drive force running through the belt and the lateral forces. The required strength of the carcass is a function of the maximum force inside the belt and the belt width. The belts should be made of a strong yet flexible material. The costs of the belt can make up to half of the price of the whole BCS. On the sides is a protective edge to protect the inner structure from being damaged. The bottom and top have a covering layer. The functions of this covers is to protect the expensive carcass. Figure 3.2 shows a schematic drawing showing the different components of the belt.

![Structure of a conveyor belt](image1)

**Figure 3.2:** Structure of a conveyor belt

3.5.2 Carcasses

As mentioned earlier the carcass needs to be strong in order to withstand the forces running through the belt. Furthermore the carcass needs to be flexible in order to be able to follow the path of the system. Two options for the construction of the carcass are a fabric or a steel cord carcass. Mazurkiewicz [2008]

![A Belt with steel cables](image2)

**Figure 3.3:** A Belt with steel cables
3.5.3 Belt cover

Depending on the field of use the belt cover needs to have specific qualities. Overall it needs to be durable and it needs to be able to protect the expensive carcass. Possible other qualities are:

- Anti-static
- Fire resistant
- Cold resistant
- Oil resistant

3.6 Idlers

The idlers are used to support the belt. They are a set of rolls where the belt runs upon. Depending on the length of the system and the weight of the load a system may have more or less idlers. In a bulk BCS its possible to use angled idlers next to each other in order to make up trough for a better form for the transportation of the bulk.

3.6.1 Idler structure

An idler consists of a frame, rolls and bearings. The belt rolls over the rolls. The bearings are used to make the roll turn smooth. The bearings are fitted on the sides of the rolls. Since idlers can break and the system usually contains of a lot of idlers they should be easily replaceable.

3.6.2 Types of idlers

Belt conveyor systems have a large amount of idlers, these can be divided up into four different types:

- trough roller
- parallel roller
- buffer roller
- self aligning roller

These can be divided into no-load and load bearing idlers. Zhao and Lin [2011]
3.6.3 Transition zone

The drive pulley is just one big roll therefore having the belt to pass it completely flat. If a trough shape for the rest of the belt trajectory is required a transition zone is made up from idlers going into a more inclined angle gradually. The length required to go from a flat belt to the desired trough shape is called the transition distance. Alspaugh [2004]

![Figure 3.4: Transition zone](image)

3.7 Pulleys

3.7.1 Drive pulley

In most cases the belt needs a form of active propulsion in order for the system to start and keep in motion. This active form of propulsion is needed to overcome the friction forces, moment of inertia and possible positive gravity forces. The drive pulley is a roller who is propelled and transforms power to the belt. The drive pulley converts the rotational speed of the drive pulley into a longitudinal speed of the belt. HOU and MENG [2008]

![Figure 3.5: Drive pulley overview](image)
3.7.2 Drive pulley structure

The pulleys are rolls with a special texture and sometimes coating in order to maximize the belt-pulley contact. The pulleys furthermore contain a shaft and bearings.

![Drive pulley](image)

**Figure 3.6: Drive pulley**

3.8 The drive unit

Belt conveyor systems need a form of propulsion somehow. This is in order to overcome the energy losses, inertial or gravitational forces. For this propulsion a drive unit is used. The drive unit applies power to the pulley who then transforms it to the belt. In most systems the drive units are electrical.

![Drive system](image)

**Figure 3.7: Drive system**

3.8.1 Drive unit components

The drive unit consists of a motor connected to a coupling. Via the coupling the power is transferred into the gearbox, which is connected to the shaft of the drive pulley. Via the drive pulley the power is eventually transmitted into the belt itself. The shaft of the drive pulley is supported by bearings on either side of the pulley.
3.8.2 Subsystems drive unit

The different subsystems of the drive unit are the motor, coupling, gearbox, shaft pulley and bearing.

**Motor**  The motor is what actually drives the systems. The motor can be driven by any form of energy, but they are mostly electric.

**Coupling**  The coupling connects the power from the drive shaft of the motor into the gearbox.

**Gearbox**  In most cases the mechanical speed of the motor will be too high in order to directly drive the drive pulley. The gearbox is used to transform the high number of revolutions of the motor into a more suitable speed for the drive pulley. By doing this the amount of torque increases. A transmission or gearbox uses gears and gear trains to convert the speed and torque of the motor to the drive pulley.

![Figure 3.8: Gearbox](image)

**Bearings**  The bearings make sure the shaft of the drive pulley is able to turn without too much friction. Usually ball bearings are used. Ball bearings consist of an inner and outer ring spaced apart by balls being able to rotate. When the inner and outer ring turn relatively to one and other the resistance only comes from the rolling of the balls.

3.9 Take-up system

The tension in the belt of the BCS is an important parameter. The tension should be within a certain level for multiple reasons.
3.9.1 Transfer power

One in order for the drive pulley being able to transform enough power to the belt. In order for the friction between the pulley and the belt to be sufficient. The friction is a function of the friction coefficient, the area of contact and the pressure. The pressure depends on the tension in the belt. Since it’s not possible to shorten or lengthen the length of the belt that easily, the system must change length. By doing so the tension in the belt can be regulated.

Belt sag Belt sag is the phenomenon of the belt of a conveyor sacking in between a set of idlers. This is a function of the distance between the idlers, the carried load on the belt and the tension in the belt. The amount of sag should stay beneath a certain limit. Lodewijks [2014]

Tension The tension is also affected by other operational aspects. Therefore it’s important to be able to control this during operation.
3.9.2 Take-up system structure

There are different types of options for a take-up system, but they all have in common that a pulley is used in order to exert a force on the belt in the outward direction of the system. In this way lengthening it, in order to increase the tension in the belt. Lodewijks [2014]

Types of take-up systems There are three major types of take-up systems:

1. Gravity take-up system
2. Winch take-up system
3. Screw take-up system

3.9.3 Gravity take-up system

The gravity take-up system makes use of gravity in order to put the proper amount of tension on the belt. The working principle is a set of pulleys and a weight that is forced down by gravity in order to put tension on the belt. A system like this varies the length of the belt in the system in order to keep the belt tension constant throughout operation.

3.9.4 Winch take up system

A winch take up system makes use of a winch to vary the length of the belt in the system, keeping the tension constant throughout operations.
3.9.5 Screw take up system

A screw take up system uses a pulley being placed further inward or outward by a screw. This lengthens or shortens the complete system. The length of the belt inside the system is therefore constant but the tension may differ throughout operation.
3.10 Brake

When a belt conveyor system needs to be stopped the power of the drive may be taken off. This does not result in a direct stop of the system tough. Due to inertial forces of the system the belt with load can roll on for quite a while. If due to safety or other reasons a faster stop is required it is possible to use a conductive motor to actively slow down the system by applying a braking force. If this still is not sufficient or in the case a back up brake is required for safety reasons, a separate braking system can be installed. Lodewijks [2014]

3.10.1 Brakes

Separate brakes can be installed to slow the system down. These will also operate when the power of the motors is off. The brakes work mechanically by the effect of friction on another surface slowing on or more of the pulleys down.
Chapter 4

Belt conveyor failure modes

In this section the reliability engineering techniques will be used to get a better and more clear understanding of the reliability of the belt conveyor system.

4.1 Schematic overview of the belt conveyor system

The system boundaries will be fixed to a single belt conveyor system. Taking into account the major sub-systems. The hopper is taken out of account and any other systems coming before or after the belt conveyor system in the total operation process. The system will be divided into several sub-systems and these into several sub-components. A system with a gravity take-up system, brake and a single drive system has been chosen.

Figure 4.1: The belt conveyor system with position of subsystems

4.1.1 Sub-systems

On the scheme (see figure: 4.1) the following sub-systems are presented:

- $S_1$ - the drive system
- $S_2$ - the belt
• $S_3$ - the idlers
• $S_4$ - the take up system
• $S_5$ - the brake system

The different sub-systems are in series (see figure: 4.2)

![Figure 4.2: The schematic overview of the system](image)

### 4.1.2 The drive system

The drive system $S_1$ composes different subsystems: motor, bearings, gearbox, coupling and drive pulley. All running in series. (see figure: 4.3)

- subsystem $S_{11}$ which consists of an electrical engine $E_{11}$
- subsystem $S_{12}$ which consists of two bearings $E_{21}$ and $E_{22}$
- subsystem $S_{13}$ which consists of gearbox $E_{31}$
- subsystem $S_{14}$ which consists of a coupling $E_{41}$
- subsystem $S_{15}$ which consists of a drive pulley $E_{51}$

### 4.1.3 The belt

The belt $S_2$ composes different subsystems: top cover, side cover and inner structure. All running in series. (see figure: 4.4)

- subsystem $S_{21}$ which consist of the top covers $E_{11}$
Figure 4.3: The schematic overview of the drive system

- subsystem $S_{22}$ which consists of the side covers $E_{21}$
- subsystem $S_{23}$ which consists of the inner structure $E_{31}$

Figure 4.4: The schematic overview of the belt
4.1.4 The idlers

The idler system $S_3$ composes different types of idlers. All running in series. (see figure: 4.5)

- subsystem $S_{31}$ which consists of a definite set with $n$ elements of parallel idlers $E_{11}, E_{12}, ..., E_{1n}$
- subsystem $S_{32}$ which consists of a definite set with $n$ elements of trough idlers $E_{21}, E_{22}, ..., E_{2n}$
- subsystem $S_{33}$ which consists of a definite set with $n$ elements of buffer idlers $E_{31}, E_{32}, ..., E_{3n}$
- subsystem $S_{34}$ which consists of a definite set with $n$ elements of aligning idlers $E_{41}, E_{42}, ..., E_{4n}$

![Figure 4.5: The schematic overview of the idlers](image)

4.1.5 The take-up system

The take-up system $S_4$ consists of two idlers and a take-up mechanism. All running in series. (see figure: 4.6)

- subsystem $S_{41}$ which consists of two pulleys $E_{11}$ and $E_{12}$
- subsystem $S_{42}$ which consists of the take up mechanism $E_{21}$ and
4.1.6 Brake system

The brake system consists of a brake system running in series with two brakes running in parallel whom themselfs run in series with brake pulleys. (see figure: 4.7)

- subsystem $S_{51}$ which consists of an electrical engine $E_{11}$
- subsystem $S_{52}$ which consists of two brakes $E_{21}$ and $E_{22}$
- subsystem $S_{53}$ which consists of two pulleys $E_{31}$ and $E_{32}$

4.2 Failure modes of belt conveyor system

Since most of the subsystems and components run in series failures of operation modes can cause the whole system to stop. [Gurjar, 2012] Below some of the failure modes of the belt conveyor will be explained in more detail. Zimroz and Krol [2009] have gathered information about occurring failures in operation.
4.2.1 Complete system

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive system $S_1$</td>
<td>Transfer enough energy to the belt</td>
<td>Unable to supply enough power or not at all</td>
</tr>
<tr>
<td>Belt $S_2$</td>
<td>Take up the power from the drive system and transport cargo</td>
<td>Not being able to take up enough power or nothing at all</td>
</tr>
<tr>
<td>Idlers $S_3$</td>
<td>Align, support and let the belt run with limited friction</td>
<td>Not being able to align, support or let the belt run with limited friction</td>
</tr>
<tr>
<td>Take-up system $S_4$</td>
<td>Take up enough of the belt to keep sufficient tension in the belt for operation.</td>
<td>Not being able to keep sufficient tension in the belt</td>
</tr>
<tr>
<td>Brake system $S_5$</td>
<td>Decelerating the belt fast enough during an emergency stop</td>
<td>Not being able to slow the belt fast enough during emergency stop</td>
</tr>
</tbody>
</table>
4.2.2 $S_1$ Belt

Since the belt of the conveyor can be the most costly part of the system a lot of research has been done on the failure of these belts. Fedorko et al. [2013]

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner structure $E_{11}$</td>
<td>Take up inner forces and tension</td>
<td>Unable to hold tension since ripped</td>
</tr>
<tr>
<td>Top covers $E_{12}$</td>
<td>Protecting the inner structure</td>
<td>Worn so that protecting the inner structure isn’t sufficient anymore</td>
</tr>
<tr>
<td>Side covers $E_{13}$</td>
<td>Protecting the inner structure</td>
<td>Worn so that protecting the inner service isn’t sufficient</td>
</tr>
</tbody>
</table>

Figure 4.8: A damaged belt
### 4.2.3 $S_2$ Drive system

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor $E_{11}$</td>
<td>Create a power in the form a rotating movements</td>
<td>Unable to rotate or insufficient rotating speed</td>
</tr>
<tr>
<td>Bearings $E_{12}$</td>
<td>Let the shafts rotate with a maximum amount of friction</td>
<td>Worn so that friction is high or completely broken</td>
</tr>
<tr>
<td>Gearbox $E_{13}$</td>
<td>Gearing the rotating movement to another angular speed and transferring the power</td>
<td>Broken tooth’s not being able to transfer the power</td>
</tr>
<tr>
<td>Coupling $S_{E_{14}}$</td>
<td>Transferring the power from the gearbox to the pulley</td>
<td>Not being able to transfer the power to the drive pulley</td>
</tr>
<tr>
<td>Drive pulley $E_{15}$</td>
<td>Transferring the rotating movement into movement of the belt</td>
<td>Transferring insufficient power to the belt</td>
</tr>
</tbody>
</table>

**Figure 4.9:** Failing of drive pulley and broken bearing

### 4.2.4 Failure mode of the idler system

The idler system is used to support and align the belt and let it roll with a limited amount of resistance.

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel idler $E_{1n}$</td>
<td>Support the belt with limited rolling resistance</td>
<td>Unable to support the belt or high rolling resistance</td>
</tr>
<tr>
<td>Trough idlers $E_{2n}$</td>
<td>Support the belt with limited rolling resistance</td>
<td>Unable to support the belt or high rolling resistance</td>
</tr>
<tr>
<td>Buffer idlers $E_{3n}$</td>
<td>Support the belt with limited rolling resistance</td>
<td>Unable to support the belt or high rolling resistance</td>
</tr>
<tr>
<td>Aligning idlers $E_{4n}$</td>
<td>Support and align the belt with limited rolling resistance</td>
<td>Unable to support and or align the belt or high rolling resistance</td>
</tr>
</tbody>
</table>
4.2.5 Failure mode of take up system

The take up system keeps sufficient tension in the belt.

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulleys $E_{1n}$</td>
<td>Pull the belt and roll with limited resistance</td>
<td>Not being able to roll with limited resistance or pull the belt to tension</td>
</tr>
<tr>
<td>Take up mechanism $E_{12}$</td>
<td>Apply tension on the pulley</td>
<td>Not applying sufficient tension on the pulley</td>
</tr>
</tbody>
</table>

4.2.6 Failure mode of brake system

The brake system is only used in an emergency and can therefore not be tested regularly. It is therefore seen as an offline function.

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency system $E_{11}$</td>
<td>Activate the brakes</td>
<td>Unable to activate the brakes</td>
</tr>
<tr>
<td>Brakes $E_{12}$</td>
<td>Apply brake force to do pulley</td>
<td>Not applying sufficient braking force</td>
</tr>
<tr>
<td>Brake pulley $E_{13}$</td>
<td>Decelerating the belt</td>
<td>Unable to take up enough energy of the belt in order to slow the system down quick enough.</td>
</tr>
</tbody>
</table>
Chapter 5

Operation modes

Operation processes of more complex technical systems tend to be very complex, therefore it is difficult to make an analysis of these systems reliability and availability with respect to their operation conditions changing in time that are often essential in this analysis. The complexity of the systems operation processes and their influence on changing in time the systems structures and their components reliability and safety characteristics is often very difficult to fix. Usually, the system environment and infrastructure have either an explicit or an implicit strong influence on the system operation process. As a rule, some of the initiating environment events and infrastructure conditions define a set of different operation states of the technical systems in which the systems change their reliability and safety structure and their components reliability and safety parameters.

Levitin

5.1 Process states

In order to get a better understanding of the system it can be divided up in different operation states. For these states we use the letter \( z \). For a system with \( v, v \in N \), different operations this would give: \( z_1, z_2, ..., z_v \). The system operations processes are also defined by: \( Z(t), t \in 0, +\infty \).

5.2 Belt conveyor operation states

The following 6 operation states are defined for the belt conveyor:

- Operation state \( z_1 \) - Steady state running
Operation state z2 - Normal operational start
Operation state z3 - Aborted start
Operation state z4 - Normal operational stop
Operation state z5 - Emergency stop
Operation state z6 - In rest

Lodewijks [2014]

5.3 Time distribution operational processes

Let’s assume an operational site where the operation is running during the day but is
being switched off during the night. The belt conveyor system will then be switched
on at the beginning of operations. A normal operational start z2. After the normal
operational start the system will run in steady state z1 during the normal operations.
When the operations are finished the system will be put in operation state z4, a normal
operational stop until it’s fully in rest z6.

In the case something is wrong during the start then the start will be aborted. The
system is going from z6 to z2 to z3 back to z6 again.

In the case an emergency stop needs to take place operation z5 is used.

During almost all of the time operational state z1 or z6 will be in use. Either having
the system running in steady state or in rest. In between these states in most cases z2
and z4 are in use. Only in rare occasions z3 and z5 are used.

Normal operation  z6 → z2 → z1 → z4 → z6

States  There were four reliability different states distinguished: (z=3)

- a reliability state 3 the system operation is fully effective
- a reliability state 2 the system operation is less effective because of ageing
- a reliability state 1 the system operation is less effective because of ageing and
  more dangerous for the environment
- a reliability state 0 the system is destroyed

To satisfy the assumption on ageing, it is assumed that transitions are possible between
the components reliability states only from better to worse. Moreover, it is assumed
that the system and its components critical reliability state is r = 2.
Since at state 1 the system will be more dangerous for the operators and therefore unwanted. Yingkui and Jing [2012]

5.3.1 Steady state running z1

During steady state running the system is in normal operation running at a constant speed transporting bulk. During this type of operation the following subsystem are used in series:

- $S_1$ the drive system, giving the belt a steady speed
- $S_2$ the belt running with bulk
- $S_3$ the idlers supporting and aligning the belt
- $S_4$ the take-up system keeping the tension in the belt sufficient

5.3.2 Normal operational start z2

During a normal operational start the system is accelerated until it reaches its desired speed. During this type of operation the following subsystem are used in series:

- $S_1$ the drive system, accelerating the belt
- $S_2$ the belt running with bulk
- $S_3$ the idlers supporting and aligning the belt
- $S_4$ the take-up system keeping the tension in the belt sufficient

5.3.3 Normal operational stop z4

During an aborted start the accelerating is aborted to slow the system down again. During a normal operational stop the drive unit is shut off and the system gradually comes to a stop due to friction. The following subsystems are used in series:

- $S_1$ the drive system is shut off
- $S_2$ the belt running with bulk
- $S_3$ the idlers supporting and aligning the belt
- $S_4$ the take-up system keeping the tension in the belt sufficient
5.3.4 Emergency stop $z_5$ and Aborted start $z_3$

During an emergency stop the brakes are activated in order to quickly stop down the system. The following subsystems are used in series:

- $S_2$ the belt running with bulk
- $S_3$ the idlers supporting and aligning the belt
- $S_4$ the take-up system keeping the tension in the belt sufficient
- $S_5$ the brake system decelerating the belt

5.3.5 System at rest $z_6$

When the system is at rest the belt has no rotating speed. The following subsystems are used in series:

- $S_2$ the belt idling
- $S_3$ the idlers supporting the belt
- $S_4$ the take-up system keeping the tension in the belt sufficient

5.4 Fuzzy logic with Bayesian

To show the working principle of the Bayesian interference described in section 2.13 combined with the use of fuzzy logic, described in section 2.14 an example on the conveyor belt system is used. This shows that the method is able to make decisions based on the monitored information.

As an example the starting $z_2$, described in section 5.3.2 in operation of a belt conveyor is considered. The values are fictive and the example is simplified by only considering two causes and dividing them into two fuzzy ranges each. The Drive system $S_1$ will be studied during the starting operation. Two states for the functioning of the starting operation will be made: $t_S$ meaning the starting time for the the conveyor belt is sufficiently fast enough and $t_L$ meaning the starting time for the conveyor belt during the starting operation is too long. The starting time of the conveyor belt depends on the abrasion of the friction profile of the pulley ($f$) and on the delivered power by the motor ($p$). The abrasion of the friction profile can be considered as low $f_l$ or as high $f_h$. The power delivered by the motor can be considered as normal $p_n$ or as low $p_l$. 
The prior probabilities of the state of the components are estimated to be like this:

\[
P(f_h) = 0.9 \quad P(f_l) = 0.1 \quad P(p_n) = 0.6 \quad P(p_l) = 0.4 \quad (5.1)
\]

It is best to use historical data for the prior knowledge. If this data is not available it is possible to use expertise in order to determine these possibilities. Data from the industry like in offshore industry gathered in a database (see section: 2.15) can also be very beneficial. If the friction profile of the pulley is worn away too far the pulley should be replaced to ensure proper operation and less damage on the belt. The motor system should be checked if the power is too low. In order to achieve the best reliability the cause of unwanted effects should be discovered. The fuzzy Bayesian interference is suitable for solving this problem with high reliability.

Lets assume the measured values from the profile of the pulley to be 14mm. The motor power is assumed to be 340kW.
Using the fuzzy logic (see section: 2.14) to better quantify these values. The assumed measured values are in between the two values to be considered a high or a low value. By using a equally weighted distribution, the fuzzy values can be calculated as.

\[ g(f_h) = 0.25 \quad g(f_l) = 0.75 \quad g(p_n) = 0.4 \quad g(p_l) = 0.6 \] (5.2)

The updated likelihood probability \( P^* \) is calculated by multiplying the value of the fuzzy membership \( g_{e_i}(x) \) with the probability of that hypothesis given that event \( e_i \). The likelihood probability is updated like:

\[ P^*(H|e_i) = g_{e_i}(x) \cdot P(H|e_i) \] (5.3)

This way the likelihood probabilities can be updated to:

\[ P^*(tS|f_h,p_n) = g(f_h) \cdot g(p_n) \cdot P(tS|f_h,p_n) = 0.09 \] (5.4)

We then also find:

\[ P^*(tL|f_h,p_n) = 0.25 \cdot 0.4 \cdot 0.9 = 0.01 \] (5.5)

\( P^*(tL|f_h,p_n) \) Means with the observation of the friction surface and the motor power the likelihood of having a long start up due to a high friction profile and normal motor power.

\[ P^*(tL|f_l,p_n) = 0.75 \cdot 0.4 \cdot 0.75 = 0.225 \] (5.6)

\( P^*(tL|f_l,p_n) \) Means with the observation of the friction surface and the motor power the likelihood of having a long start up due to a low friction profile and normal motor power.

\[ P^*(tL|f_h,p_l) = 0.25 \cdot 0.6 \cdot 0.55 = 0.0825 \] (5.7)

\( P^*(tL|f_h,p_l) \) Means with the observation of the friction surface and the motor power the likelihood of having a long start up due to a high friction profile and low motor power.

\[ P^*(tL|f_l,p_l) = 0.75 \cdot 0.6 \cdot 0.95 = 0.4275 \] (5.8)
\( P^*(t_L|f_l, p_l) \) Means with the observation of the friction surface and the motor power the likelihood of having a long start up due to a low friction profile and low motor power.

With the updated likelihood probabilities the posterior probabilities of \( f \) and \( p \) can be calculated.

\[
P(f_h, p_n|t_L) = \frac{P^*(t_L|f_h, p_n) \ast P(f_h) \ast P(p_n)}{P^*(t_L)} = 0.082 \tag{5.9}
\]

\( P(f_h, p_n|t_L) \) Means the chance of the long starting time being caused by high friction and normal motor power.

\[
P(f_l, p_n|t_L) = \frac{P^*(t_L|f_l, p_n) \ast P(f_l) \ast P(p_n)}{P^*(t_L)} = 0.206 \tag{5.10}
\]

\( P(f_l, p_l|t_L) \) Means the chance of the long starting time being caused by low friction and normal motor power.

\[
P(f_h, p_l|t_L) = \frac{P^*(t_L|f_h, p_l) \ast P(f_h) \ast P(p_l)}{P^*(t_L)} = 0.452 \tag{5.11}
\]

\( P(f_l, p_l|t_L) \) Means the chance of the long starting time being caused by low friction and low motor power.

\[
P(f_l, p_l|t_L) = \sum_{i,j} P^*(t_L|f_i, p_j) \ast P(f_i) \ast P(p_j) = 0.0054 + 0.0135 + 0.0297 + 0.0171 = 0.0657 \tag{5.13}
\]

The outcome of \( P^*(t_L|f_l, p_l) = 0.4275 \) suggests that starting time should be expected long because of the wear of the friction pad of the idler and the low power of the motor. The long starting time however is mainly due to the lack of motor power as can be seen by \( P(f_L|f_h, p_l) = 0.452 \). This one has the highest value of the four posterior probabilities. Meaning that the main cause for the effect of a long starting time is the motor power. This allows the system to tell that maintenance should be done on the motor.
As can be seen by combining the fuzzy logic with Bayesian belief network the causes of effects can be determined in a very efficient way. This information can be used in order to increase the overall reliability by making the right decisions in the processes.
Chapter 6

Automated reliability optimization

A major goal in industry is the optimization of the reliability of operation systems. In order to be safer, more reliable and more cost effective. In a lot of industries a lot of progress has been made on this part. As is seen in the preceding chapters a belt conveyor system is a complex system with a whole lot of subsystems and components running in series. The most easy way to improve the overall reliability of the operation is in the form of complete redundancy. By putting a second conveyor belt system next to the system in order to use as a backup in the case the first one fails. Since cost is the major concern this is certainly not always the best option. Other sectors have used reliability centered maintenance approaches combined with automated monitoring and decision making in order to do predictive maintenance. This technique makes the system a more smarter system and increases reliability. At this moment in time the advanced technology of reliability centered maintenance in industrial sectors like offshore engineering Mousavi et al. [2013], aircraft and power-plant industries is widely implemented. In Conveyor belt systems this is not yet the case. Currently little or no predictive maintenance is done in conveyor belt systems. Lodewijks and Ottjes [2004]

For improving the overall reliability of belt conveyor systems the design and the maintenance strategy can be shifted more towards the predictive maintenance. There are four type of maintenance strategies: Lodewijks and Ottjes [2004] random maintenance, corrective maintenance, preventive maintenance and predictive maintenance. The use of predictive maintenance is the most advanced. The system will be designed to monitor the different components of the belt conveyor system and the degradation of parts is
predicted. At this way maintenance can be scheduled to improve the overall reliability of the system. This condition based strategy allows for intelligent and automated maintenance.

The eventual goal is to have a system with automated monitoring of the belt conveyor components, coupled with automated decision making systems. Lodewijks [2014]

In the following section some of the modern systems for automated monitoring of different components of the system will be explained. Later on new techniques for automatic decision making will be explained.

6.1 Conveyor belt system monitoring

In order to get insight about the current state of the system monitoring is very important. This can be automated to be a lot more effective, cheaper and faster.

6.1.1 Automated belt conveyor monitoring

The traditional belt conveyor monitoring and the maintenance focus on the response of failure or abnormality of single components. With this working method detection of problems is very late in the process not really enhancing the overall reliability of the system. An automated belt conveyor monitoring system could detect small changes and fluctuation in the system. By processing and analysing these subtle changes a mechanical or electrical problem starting to develop can be derived. This allows for prediction of possible following system failures. When the monitoring and decision making is extended to a system level instead of separate component or sub-system level the decisions can be made better in order to improve and optimize overall system reliability.

There have been advances in the development of systems that could be used for conveyor belt monitoring. There are various techniques available to measure different type of components occurrences. Some sensors measure directly, other indirectly.

Aspects which can be monitored are:

- Belt condition
- Belt speed
- Torque
- Vibration
- Power
• Belt alignment
• Temperature

The monitoring of these components and aspects works via various different techniques:

<table>
<thead>
<tr>
<th>Parameter/aspect</th>
<th>Component</th>
<th>Sensor/technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt condition</td>
<td>Surface</td>
<td>Visual detection</td>
</tr>
<tr>
<td></td>
<td>Steel cables</td>
<td>Conductive detection</td>
</tr>
<tr>
<td>Speed</td>
<td>Belt</td>
<td>Optical/magnetic encoder</td>
</tr>
<tr>
<td></td>
<td>Brake disk</td>
<td>Magnetic RPM pickup sensor</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Motor shaft</td>
<td>Torquemeter</td>
</tr>
<tr>
<td></td>
<td>Brake shaft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulley shaft</td>
<td></td>
</tr>
<tr>
<td>Force &amp; Tension</td>
<td>Take-up</td>
<td>Strain gauge</td>
</tr>
<tr>
<td></td>
<td>Belt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frame</td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>Pulley</td>
<td>Acoustic vibration sensor</td>
</tr>
<tr>
<td></td>
<td>Idler roll</td>
<td>Accelerometer</td>
</tr>
<tr>
<td></td>
<td>Rotating drive/brake system components</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>Motor</td>
<td>Watt meter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torque sensor</td>
</tr>
<tr>
<td>Position</td>
<td>Belt misalignment</td>
<td>Alignment switch</td>
</tr>
<tr>
<td></td>
<td>Take-up displacement</td>
<td>Optical encoder</td>
</tr>
<tr>
<td>Temperature</td>
<td>Ambient</td>
<td>Thermocouple</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Infrared temperature sensor</td>
</tr>
<tr>
<td></td>
<td>Belt cover</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brake disk</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulley shaft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td></td>
</tr>
</tbody>
</table>

In the next subsection these techniques are explained in more detail.

6.1.2 Belt monitoring

Belt condition of the conveyor belt system is made up out of the conditions of the two components: the inner structure and the covers.
Belt interior monitoring  The most popular technique of monitoring the interior of the belt is by conductive monitoring. The working principle of this technique is a set of conductors which generate or reflect a signal to one or more detectors. The conductors are usually embedded into the inner structure of the belt. The conductors can be in the form of conductor loops, coils or magnets. The detectors are placed on the traveling parts of the conductors making no contact to the belt. The time between following conductors is measured. Later this can compared with the speed of the belt and the set distance between the conductors. This gives information about the spacing in the inner structure. Hauer et al. [2013]

![Monitoring system to check inner belt structure](image)

Figure 6.1: Monitoring system to check inner belt structure

Belt surface monitoring  In order to monitor the belt surface cameras can be used. These images can be manually inspected by a specialist. To automate this process, high speed cameras connected to computer systems can be used for pattern recognition. The most important part parts in the automated processing of the images is the image processor which enables the automatic processing of the images. Yang et al. [2014]

Speed monitoring  With the measurement of belt speed none of the wearing aspects of the components is directly measured itself, but it will tell a whole lot about the system. The monitoring is necessary to determine if the belt is running at the desired speed, but also to verify the starting and stopping dynamics of the conveyor belt system. [Lodewijks, 2014] The rotational speed of the motor, pulleys and brakes will tell about the performance of those components when measured.

One way to measure both the rotational speed of the components and the belt speed, is by using angular encoders. These work by a round wheel with holes where light can pass true. On the other end is a receiver, when it receives light it knows a whole has passed. By knowing the spacing between the holes and equally space them along the rotation the angular speed can be derived. In order to measure the belt speed a tachometer is used. This is an angular encoder with a wheel that touches the belt in order to translate the directional speed measurement into a rotational one.
6.1.3 Force tension and torque measurement

In order to measure the tension or torque, the fact that under strain a material deforms is used. By knowing the characteristics of the material, the amount of deformation can be transformed into the stress and the applied force. By performing measurements like this the amount of stress on components and the system can be measured. The amount of deformation can be measured with the use of a strain gauge. 6.5 A strain gauge 6.4 is a resistor that changes resistance when its elongated. The difference in resistance is a measure for the amount of elongation. By measuring this amount the stresses and forces can be determined. Zimroz and Krol [2009]
6.1.4 Vibration monitoring

When components of the belt conveyor system oscillate around their equilibrium points vibration occur. Components like the gearbox, pulleys, idler roll, motors and bearings whom rotate or have rotating parts show these vibrations. By measuring the amount of these vibrations, insight can be obtained about the status and operational state of these components. Lodewijks and Ottjes [2004]

In order to measure these vibrations the sound generated by the oscillation of the components can be used. By measuring and analysing the sound pattern. The acoustic waves form a complex system set of different frequencies. By translating these with a Fourier transformation into the frequency domain these can be better analyzed. Zimroz and Krol [2009]

6.1.5 Power monitoring

In order to get more insight on the operation efficiency, losses or the torque and power a monitoring of the engine can be used. By using a wattage meter connected to the power
supply the amount of energy can be measured. This is a product of the input voltage and the amount of current in amperes going into the system.

6.1.6 Misalignment monitoring

Belt misalignment can cause the belt to run out of the rollers and causing severe damage to itself and other parts of the system. This may also lead to unsafe situations. Therefore monitoring this is an important parameter. In order to measure this, switches on the side of the belt can be placed. By placing these at a position where they are switched once the belt goes passed a critical point the system will be noticed once the belt goes out of center too much.

![A switch to check alignment](image)

**Figure 6.6:** A switch to check alignment

6.1.7 Temperature monitoring

The temperature of moving components in the system can be measured by infrared sensing. A body will have radiation waves coming off from its surface, the frequency of these waves depends on the temperature of the surface. By measuring the frequency of the waves of the radiation the temperature of the component can be derived.

6.2 Decision making

With real time and life data and an historical database of failures the next step is automated decision making.
The effectiveness of a conveyor belt diagnostic system primarily depends on the use of a decision supporting system. Mazurkiewicz [2015] With adequate inference rules applied, this system would increase the effectiveness and shorten the time of decision-making as well as verify generated signals. The above tasks can be performed by a suitable expert system that predicts values of the analyzed time series, using the predicted values and inference rules to verify any potential false alarm signals at the same time.

The effectiveness thus majorly depends on the decision system. With adequate inference rules applied, this system would increase the effectiveness and shorten the time of decision-making as well as verify generated signals. The above tasks can be performed by a suitable expert system that predicts values of the analyzed time series, using the predicted values and inference rules to verify any potential false alarm signals at the same time. Although all standard classification and estimation methods can, under certain conditions, be also employed for prediction. Mazurkiewicz [2015].

![Diagram](image)

**Figure 6.7:** An automated decision system (b)

The conveyor transport system is an object that is affected by a number of factors. These factors are either imprecisely determined or difficult, if not impossible, to measure because of their random and incidental nature. This object is hard to describe owing to its dependence on numerous unpredicted variables that are often additionally difficult to be precisely determined. Failure-signaling symptoms can occur either once or many times; they can also have different intensity and nature. Another common problem here is lack of unambiguous information about the analyzed object and the required short time of a potential reaction. When equipping a comprehensive conveyor transport system with efficient and advanced monitoring and diagnostic systems, it is therefore necessary that sophisticated and intelligent tools be used to support the above. Mazurkiewicz [2015] The state of the art solution for monitoring belt conveyor systems would be an intelligent
system that integrates the individual measurements of the system and integrates them into one overall system, enabling decisions for maintenance and improvement to be made at system level. This intelligent system would overcome the inability of humans to automatically acquire and interpret data and information from the belt conveyor system. In order to achieve these functions in a way without or less human efforts, different kind of artificial intelligence, which have been widely applied in other sectors can be employed. Pang and Lodewijks [2006]

6.2.1 Artificial intelligence

Mostly artificial intelligence is mostly described as non-algorithmic reasoning and automatic decision making and problem solving.

- Intelligence is the calculative and deductive abilities, which are based on acquired data and information;
- Intelligence is the probabilistic abilities to reason with uncertainty and fuzzy logic, which are considerably contained in acquired information;
- Intelligence is the inference architecture of the human brain, which can be represented as neural network or belief network for reasoning in complexity;
- Intelligence is the intuition of human beings in making decisions based on stored and reusable knowledge and experience;
- Intelligence is the structure of human relationships, which is organized both locally and globally to form the integration of individual communities;

6.2.2 Assessment for intelligent monitoring system

In order to see whether artificial intelligence would be a feasible solution for the belt conveyor system certain assessment tests have been developed. Studies show that it’s feasible to use artificial intelligence for conveyor belt monitoring and decision making [Pang and Lodewijks, 2006]

6.3 Reliability optimization

By implementing reliability centered maintenance in combination with automated conveyor belt monitoring and the automated decision making systems all ready being used in other sectors, predictive maintenance can be performed. This will allow for scheduled and efficient maintenance and operation. Increasing the overall reliability and saving
costs. As shown in this chapter many monitoring solutions are available. Joined with fuzzy logic a Bayesian Belief Network and artificial intelligence this could lead to completely automated decision making. This leads to a system as can be seen in figure: 6.7 under b. Increasing the precision and speed of the reliability centered maintenance to a level impossibly achieved by human experts. Therefore further increasing the total level of reliability for the system. Maintenance tasks can be scheduled instead of letting the system run to a breakdown. Due to the system structure of a belt conveyor system with a lot of components and sub-systems in series this would almost certainly lead to a breakdown of the complete system. This breakdown would then occur during normal operation. Possibly causing more than just the conveyor belt system itself to stop functioning.
Chapter 7

Conclusion

In this report the belt conveyor system is explained and there has been looked at the number of different sub-components this systems has. The system contains a lot of components in series running in very hard operating conditions. In current belt conveyor systems reliability could be improved since systems mostly just run to failure instead of having a thought of system for the maintenance of the components and sub-systems. Due to the design of belt conveyor systems it is hard and it would be very costly to just add a lot of redundant components. The future to improve reliability of these complicated systems is better to be found by using predictive maintenance systems all ready used in other industries. In for example offshore engineering, aerospace and power plants, predictive maintenance has proved to improve the reliability of a system by decreasing the downtime. Maintenance can be better scheduled and components can be better used improving durability and the efficiency of the system in operation. The state of the art solution for predictive maintenance has shown to be an automated monitoring system. A system being able to continuously track the components during operation. Currently research is done on these monitoring systems. Since the belt conveyor systems have to operate under harsh conditions these have to be very strong and tough systems. With the continuous live data of the belt conveyor system under operation send to an automated system evaluating the data. And then automatically decision making based on the evaluated data would be the most state of the art solution. A Bayesian Belief network combined with the use of fuzzy logic can be used to more easily analyze the operation states by constantly updating the different input values. In combination with the possible use of artificial intelligence, which is shown to be a feasible solution in this field, the automated decision system should be possible.
7.1 Recommendations

In order make the automated predictive maintenance systems a reality. Especially in
the hard operations of belt conveyor systems more research and development has to be
done on the following: The available monitoring techniques should be further improved.
Artificial intelligence algorithms should be specifically developed for the belt conveyor
systems. Further research has to be done on how to properly interpret all the acquired
data. The eventual effects look promising as all ready shown in other industries. Allow-
ing to further improve the overall reliability of the belt conveyor systems.
Bibliography


