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Title: Methods and Applications of Reliability Control for Conveyor Belt Systems

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Subject: Methods and Applications of Reliability Control for Conveyor Belt Systems

Reliability control reduces unplanned system downtime and unreliable operations caused by malfunction of system and components and equipment. Reliability control concerns the monitoring, assessment methods and maintenance strategies.

This assignment will focus on the reliability control of conveyor belt systems in the Transport Engineering and Logistics domain. This literature assignment will cover:

- The concept of reliability control
- The concept of reliability of conveyor belt systems
- Methodologies for reliability control of conveyor belt systems
- Applications for reliability control of conveyor belt systems
- Benefits of reliability control of conveyor belt systems

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 Transport Engineering and Logistics section.

The supervisor,

Dr. ir. X. Jiang
Summary

Conveyor belt systems are widely used equipment in many different industries to transport goods onsite. Conveyor belt systems often consist of a drive unit with pulleys, a belt and multiple idlers to support the belt. All these individual components can fail and lead to a stop of the system. Operators of conveyor belt systems want to know when failure is about to happen, so the optimal moment for maintenance activities can be planned.

In reliability control fault and failures should be diagnosed, a prognosis should be made and a suitable maintenance strategy should be chosen. The focus of reliability control is to control a system to let it perform the required function under stated conditions for a stated period of time.

In the design stage of a conveyor belt system the operational and lifetime requirements have to be determined. Based on these requirements the conveyor belt system should be designed. Methods like finite element method or discrete element method can be used to check the requirements in the design.

During operation of the conveyor belt system monitoring techniques can be applied to monitor the condition of the conveyor belt. Supported with assessment methods signs of premature failure should be noticed and the control system should take actions to still get to the next planned stop.

Applying a reliability control system to a conveyor belt system will result in reduced operational costs and maintenance costs, increased productivity and better reliability.

There are still some challenges remaining before the complete conveyor belt system can be reliability-based controlled. Examples are the interpretation of the huge amount of data acquired from the monitoring equipment, uncertainties in measurement equipment and uncertainties in the prediction of failures.

An optimum should be found between the investment costs of the reliability control system and the return on investment. Adding more and more complex control systems will not automatically result in optimal gains.

New developments like robotic maintenance and monitoring equipment, using the internet of things principle or computer aided maintenance management systems can help to successfully apply reliability-based control for conveyor belt systems.
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<table>
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>F</td>
<td>Functional failure</td>
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<tr>
<td>P</td>
<td>Probability</td>
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<td>P(A)</td>
<td>Probability of event A</td>
<td>[%]</td>
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<tr>
<td>R</td>
<td>Reliability</td>
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<td>(S_{\text{ref}})</td>
<td>Reference spacing</td>
<td>[m]</td>
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<tr>
<td>T</td>
<td>Time</td>
<td>[s]</td>
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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AG</td>
<td>Aktiengesellschaft</td>
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<tr>
<td>BCM</td>
<td>Belt Conveyor Monitoring</td>
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<tr>
<td>BCS</td>
<td>Belt Conveyor System</td>
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<tr>
<td>BWE</td>
<td>Bucket Wheel Excavator</td>
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<tr>
<td>CMMS</td>
<td>Computer-aided Maintenance Management System</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>DAC</td>
<td>Decentralized Autonomous Corporation</td>
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<tr>
<td>DCOM</td>
<td>Distributed Component Object Model</td>
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<tr>
<td>DEM</td>
<td>Discrete Element Method</td>
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<tr>
<td>DM</td>
<td>Data Mining</td>
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<td>DTS</td>
<td>Distributed Temperature System</td>
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<tr>
<td>ETA</td>
<td>Event Tree Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FFOP</td>
<td>Failure Free Operating Period</td>
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<td>FMEA</td>
<td>Failure Mode and Effect Analysis</td>
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<tr>
<td>FTA</td>
<td>Fault Tree Analysis</td>
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<tr>
<td>HAC</td>
<td>High Angle Conveyor</td>
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<tr>
<td>IMIR</td>
<td>Intelligent Maintenance of Idler Rolls</td>
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<tr>
<td>Inc</td>
<td>Incorporation</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>MAR</td>
<td>Machinery, Automation &amp; Robotics</td>
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<tr>
<td>MFOP</td>
<td>Maintenance Free Operating Period</td>
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<tr>
<td>MTBCF</td>
<td>Mean Time Between Critical Failure</td>
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<td>MTBF</td>
<td>Mean Time Between Failure</td>
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<td>MTBM</td>
<td>Mean Time Between Maintenance</td>
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<td>MTBO</td>
<td>Mean Time Between Overhaul</td>
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<td>MTBUR</td>
<td>Mean Time Between Unscheduled Removal</td>
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<tr>
<td>MTTF</td>
<td>Mean Time To Failure</td>
</tr>
<tr>
<td>MTTR</td>
<td>Mean Time To Repair</td>
</tr>
<tr>
<td>PRM</td>
<td>Progressive Reliability Method</td>
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<tr>
<td>PVC</td>
<td>Poly Vinyl Chloride</td>
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<tr>
<td>RBD</td>
<td>Reliability Block Diagram</td>
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<td>RFID</td>
<td>Radio Frequency Identification</td>
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<td>RIC</td>
<td>Robotic Idler Change-out</td>
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<tr>
<td>RPN</td>
<td>Risk Priority Number</td>
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<td>SS</td>
<td>Safety System</td>
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1. Introduction

Conveyor belt systems are widely used transport machines. Belt conveyors are used in many different industries, such as mining, cement and lime production, natural resource processing, pulp and paper production, agriculture, power plants, sea and river ports, sugar factories and civil engineering.

Due to the flexible transport system configuration, simple and light construction, high efficiency, ease of installation in variable landscape conditions and the possibility to transport goods over considerable distances, conveyor belt systems are a preferred means of transport. Besides goods, conveyor belt systems can also be used to transport loose materials with various chemical and physical characteristics. [1]

From time to time conveyor belt systems need maintenance or components need to be replaced. To keep the conveyor belt system running, the reliability of the system needs to be controlled. The reliability control concerns system monitoring, assessment methods and maintenance strategies.

This report starts with some global information about conveyor belt systems. In the third chapter, the methods of reliability control for conveyor belt systems are discussed. The following chapter goes in to applications of reliability control and states the current state and remaining challenges. The next chapter discusses the opportunities and benefits of reliability control. The report ends with a conclusion based on the findings in the report.
2. **Conveyor belt systems**

Conveyor belt systems are widely used for continuous onsite transport. Conveyor belt systems can have large conveying capacities and can transport different type of goods and materials. It is used in mining industries, in baggage handling systems, chemical industries, ports, food supplies and many other industries. [2] [3]

2.1. **History and development**

The first conveyor belt systems date from the late 18\textsuperscript{th} century. A hand crank coupled to a pulley was used to move a rubber belt over wooden beds. The first application of this type of conveyor belt was the transport of farmer goods onto ships at a port.

The invention of the steam engine lead to the replace of man-powered conveyor belts to by steam powered conveyor belts. The first application of a steam powered conveyor belt was in 1804 by the British Navy, in a factory that made biscuits for their sailors.

In 1901 in Sweden the first steel belt was invented which was used to transport gravel and charcoal. In Ireland in 1905 the first underground conveyor belt system was applied for mining activities.

In 1908 the roller conveyors were invented, which allowed smooth transport of goods and materials by means of internal bearings in the rollers.

Henry Ford was the first to apply a conveyor belt system in the assembly of products in 1913. He used a conveyor belt system to transport the Ford Model T car through the assembly line, as shown in Figure 1. The transport of the car along the assembly line allowed workers to stay at one place at the assembly line and do only one specific assembly job. This reduced the assembly times of the car greatly. Conveyor driven assembly became the standard for car production by 1919.

![Figure 1 Ford model T's on a conveyor belt in the assembly line [4]](image)

The Second World War boosted the development of synthetic materials due to the lack of natural resources such as cotton and rubber. Urethane and synthetic rubbers were developed and new shapes for the belt assemblies where applied to increase the efficiency of conveyor belt systems.
In 1957 the B.F. Goodrich Company patented the first turnover belt, which allowed a longer lifetime of a conveyor belt by reducing the wear. Figure 2 shows the turnover belt principle compared to a conventional conveyor belt configuration, based on spillage of material. [5]

![Figure 2](image2.png)

*Figure 2 Top: conveyor belt system without turnover, bottom: system with belt turnover [6]*

In the 70s of the 20th century, Intralox patented the modular plastic belt. With a modular conveyor belt, plastic modules can be linked together with rods. This allows different layouts of a conveyor belt. [7] At the same time the development of the pipe conveyor started. A pipe conveyor enables encapsulated transport of a material, the material and tube move together. Material is dropped onto a flat belt, which is then formed into a pipe shape, as shown in Figure 3. At the end of the line the belt unfolds, and material is released from the belt in for example a hopper. In 1979 the first pipe conveyor was installed for commercial purposes at Kitakyushu Sand Co-op in Japan. [8]

![Figure 3](image3.png)

*Figure 3 A schematic view on a modern pipe conveyor system of Bridgestone [9]*

Also different techniques were developed to enable vertical displacement of materials and goods. An example of a belt developed for this purpose is the High Angle Conveyor (HAC) of Continental AG, which is a sandwich conveyor belt system. The principle is shown in Figure 4, the material is sandwiched in between a top and a bottom belt.

![Figure 4](image4.png)

*Figure 4 The principle of a sandwich conveyor belt [10]*

Another example of a conveyor belt system for vertical transportation of materials is the pocket lift, also developed by Continental AG. The material is stored in pockets and can be transported vertically, as shown in Figure 5.
At first conveyor belt systems were only powered at the start of the conveyor belt system, but in 1974 Kaiser Coal started to distribute the power input by placing drives spread over the length of the conveyor belt system. This resulted in an increased efficiency and the possibility to transport material over a longer distance with just one conveyor belt system. This meant the shift to steel cord reinforced belts, which can handle the increased strength requirements of the longer conveyor belt systems. [12]

The conveyor belt found its way into the first automated baggage handling system in 1971 by BNP Associates Inc. A baggage handling system can transport baggage from the baggage drop-off place to the airplane or vice versa. The system is able to identify and sort the baggage to deliver them at the correct location. An example of a baggage handling system is shown in Figure 6. After the terrorist attacks in 2011 on September 9th governments required baggage screening before entering the airplanes, so screening and inspection technologies have been implemented in the baggage handling system since then.

The increased performance of computers leads to new opportunities like the simulation and analysis of the dynamical behavior of conveyor belt systems. The stresses in the belt during for example starting and stopping can be established and a suitable belt can be chosen to fit the requirements. [12] Nowadays different techniques are applied to monitor and assess the condition of a conveyor belt system, this will be discussed in section 3.
2.2. **Principal components of a conveyor belt system**

A conveyor belt system commonly consists of two or more pulleys, also called drums. An endless carrying medium rotates about the pulleys, this is the conveyor belt. To move the belt over the pulleys, one or more pulleys are powered. The powered pulleys are also called the drive pulleys, the unpowered pulleys are the idler pulleys or idler rollers. In some conveyor belt systems covers are placed over the belt to prevent the spread of dust. [14]

With a loading hopper the material that needs to be handled by the conveyor can be dropped onto the belt. At the end of the conveyor belt system, the material falls from the belt into the unloading hopper or onto the next conveyor belt if the system consists of more than one conveyor belt. Some conveyor belt systems are also equipped with belt cleaning systems. An example of a possible conveyor belt system is given in Figure 7.

![Example of a possible conveyor belt system](image)

*Figure 7 Example of a possible conveyor belt system [15]*

The main components of a conveyor belt system can be divided in three categories: the drive unit, the belt and the idlers.

### 2.2.1. **Drive unit and pulleys**

The drive unit applied in a conveyor belt system often consists of an electric motor, a damping coupling, a gearbox, some bearings, a coupling that connects the output shaft to the pulley, the pulley(s) and in some cases a brake system. A schematic view of a possible drive unit is given in Figure 8. [16]

![Drive unit](image)

*Figure 8 Drive unit [16]*
To be able to stop the conveyor belt, some drive units have a brake system between the electric motor and the gearbox, as shown in Figure 9.

![Figure 9 A different drive unit: 1 - motor, 2 - brake drum, 3 - flexible coupling, 4 - gearbox](image)

In the drive unit different pulleys can be used, for example steel drum pulleys, spun end curve crown pulleys, spiral drum conveyor pulleys, welded steel pulleys with diamond grooved lagging, welded steel pulleys with grooved lagging or spiral wing conveyor pulleys. These are illustrated in Figure 10.

<table>
<thead>
<tr>
<th>Steel drum pulley</th>
<th>Spun end curve crown pulley</th>
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<tr>
<td>Spiral drum conveyor pulley</td>
<td>Welded steel pulley with diamond grooved lagging</td>
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</table>
2.2.2. Belt

The belt often consists of an upper and lower cover and a core with steel cables. Figure 11 schematically shows a belt with a steel cable core.

There are many different conveyor belt types for different applications, some of them are:

- **Standard rubber belts**
  Standard belts are suitable for the handling of most abrasive materials. The belt is made out of a blend of natural and synthetic rubber.

- **Cut resistant belts**
  The rubber used for cut resistant has a high content of natural rubber. The belts operate under conditions where cutting and gouging of covers may occur.

- **Heat resistant belts**
  Heat resistant belts are used to handle materials with temperatures up to 1200°C. Covers with styrene butadiene are applied.

- **Super heat resistant belts**
  Super heat resistant belts have can handle materials with temperatures of up to 1700°C. The cover is often made out of Chlorobutyl.

- **Fire resistant belts**
  Covers containing neoprene with multi-ply carcass constructions are applied in fire resistant belts.

- **Wood handling belts**
  The wood handling belts are developed for the timber industry with high resistance to resin and oil.
• Food quality belts
  The food quality belts use non-toxic materials resistant to fats, oils and staining for the food processing industry.

• Oil resistant belts
  Oil resistant belts are easy to wash due to linings in neoprene, synthetic or nitrile rubber. These belts can be applied in handling vegetable oils and minerals.

• Concentrator belts
  These belts are specially used in gold mine concentrators, to separate the gold from the collected material by means of vibrations.

• PVC solid woven belts
  In PVC solid woven belts are made out of nylon and polyester with cotton soaked in armor of PVC and PVC coatings.

• Nitrile covered PVC belts
  Nitrile covered PVC belts have properties of flame retardant, heat, oil and abrasion resistance.

• Steel cord belts
  In long distance conveyor belts, belts with a steel cord carcass are applied. These conveyor belts are stiffened with a steel wire within a high-quality rubber. These belts can withstand high material impact and high traction loads.

• Steel belts
  Steel belts can be applied in high temperatures, vacuum or caustic environments.

• Fire resistant steel cord belts
  Fire resistant steel cords belts have properties to self-extinguish fire.

• Chevron standard belts
  In chevron standard belts steel tire cords in a V-shape at intervals over the belt length. These belts are applied in the handling of materials in difficult conditions i.e. slag transportation.

• Corrugated sidewall belts
  In confined spaces corrugated sidewall belts can be an effective way of elevating materials. These belts are commonly used in coal-fired power plants, ports, chemical industry and cement plants.

2.2.3. Idlers

Different types of belts ask for different idlers, i.e. flat belts or troughed belts. For a troughed belt the belt should troughed properly, so the angle of the troughed belt should build up in small steps, like Figure 12.
In the troughed belt conveyor different types of idlers are applied, the three in-line idler rollers, the impact idlers and the return idlers.

The in-line idlers rollers are applied throughout the belt to carry the load on the belt. An example of this idler type is given in Figure 13.

The impact idlers are applied in regions where the load is dropped onto the belt, in the loading points. An example is given in Figure 14.

The return idlers are used to support the returning belt without load. An example of a return idlers is given in Figure 15.
Idlers can be placed in different configurations as illustrated in figure 7.

![Diagram of idler configurations](image)

**Figure 16** A idler set supporting driving strand, 1 - two-idlers, 2 - three-idlers, 3 - five idlers, B - idlers set supporting driven strand, 1 - Idlers in V-arrangement, 2- idlers with cleaning rubber rings in V arrangement [17]

### 2.3. Section summary

The conveyor belt system is applied since the late 18th century and has found its way into many different industries. The principal components of a conveyor belt system are the drive unit and pulleys, the conveyor belt and the idlers. Many different types of pulleys, idlers and belts can be chosen for a specific conveyor belt system, depending on the application of the specific system.


3. Methods of reliability control for conveyor belt systems

This section will discuss the control methods that are currently applied for conveyor belt systems. Also reliability control will be defined, failures of the conveyor belt system will be addressed and different methods to apply reliability control will be discussed.

3.1. Control methods for conveyor belt systems

Conveyor belt systems are critical equipment for many companies: when a conveyor belt stops, the production or the supply of materials stops too. There are multiple ways to control a conveyor belt system.

3.1.1. Human control

A simple conveyor belt system is often controlled by a human operator. He sets the speed of the conveyor belt with a control circuit (often a frequency controller) coupled to the drive unit. In this simple set up, as shown in Figure 17, no computer- or sensor technologies are applied to monitor and assess the condition of the conveyor belt. The operator will have to use his eyes and ears to assess if the conveyor belt system is still operation according to the operational requirements.

![Figure 17 A simple control system for a conveyor belt system [18]](image)

3.1.2. Computer-aided control

Conveyor belt systems can also be controlled by human operators who are supported by computers and measuring equipment. An example of a more advanced control system for a conveyor belt system is given in Figure 18. This system is started manually by pressing a start button. It can determine belt tear and misalignments, slip in the belt, temperature deviations in the drive units and can also monitor external environmental conditions like the CO content in the air. If some of the parameters exceed
predefined limits the conveyor belt can be stopped automatically by the system. Along the belt a safety cord is placed as well, so an operator can manually stop the belt if he recognizes a (critical) failure.

![Diagram of conveyor belt control system](image1)

*Figure 18 A conveyor belt control system of Davis Derby Ltd. [19]*

The systems are often only to some extent reliability-based, so no data is used about component failure. The optimal moment for maintenance is often not determined by the control system itself. An example of a system which does have some reliability-based control, is made by CBM Conveyor Belt Monitoring in Australia, as shown in Figure 19. This system diagnoses the condition of the conveyor belt and gives a rough estimation about the remaining lifetime of the belt, based on history data of the belt. The human operator has to decide based on the expected lifetime at which moment maintenance is needed.

![Diagram of CBGuard Life Extender X5](image2)

*Figure 19 The CBGuard Life Extender X5 of Conveyor Belt Monitoring [20]*
3.1.3. Improvements

A conveyor belt system is composed of several components and the maintenance process is not trivial and is often corrective based. This means only maintenance activities are applied when a component of the system fails.

Operators of large-scale bulk handling facilities try to schedule preventive or predictive maintenance based on the results of visual inspection and signals from installed sensor systems, knowledge of the history of the system and the operational possibilities for a controlled shut down. [21]

It is a challenge to guarantee the operation of conveyor belt systems due to the large number of components spread over great distances. Some parts are clustered at the head and tail of the conveyor belt, but along the belt a large number of components (for example the idlers) are installed as well. The idlers can be hard to monitor and service over large distances and so broken idlers can go unnoticed. Inspectors are often used to manually check the condition of the idlers along the belt and to trigger maintenance activities. Human inspection can lead to a wide range of problems, for example tying errors, wrongly or too late ordered components or failed components that have been overseen. [22]

A lot of money is lost when a conveyor belt system fails. This often occurs due to the lack of appropriate mechanisms for efficient monitoring, lack of assessment methods that help to assess the condition of the system and inappropriate maintenance strategies. [22]

Operators try to plan maintenance activities during scheduled stops, but very often the system has to be stopped during operation due to unexpected failures. [23] To lower the operational and maintenance costs and to guarantee the expected operational life, better control methods should be applied.

3.2. Reliability control defined

Reliability of a system or component is defined as ‘the ability to perform its required function(s) under stated conditions for a stated period of time’. [24] It can be expressed as a ‘projection of quality over time, meeting customer’s expectations over its life time’. [25]

Reliability control focuses on the control of a system to let it perform the required function under stated conditions for a stated period of time. Required function, ability, conditions and specified period of time are key elements in the definition. The required function is related to the expected performance, the ability is quantified with probability. Conditions usually refer to the environmental conditions of operation. The specified period of time refers to the expected operational time (of a system). Reliability (R) is mathematically defined as the probability (P) that the random variable time to failure (T) is greater or equal to the expected operational time (t). [25]

\[ R(t) = P(T \geq t) \]
To achieve reliability of a product, reliability has to be specified. The design of the product has to fulfil the reliability requirements. In the verification and validation stage of a product development, the reliability of the product has to be tested. In the manufacturing stage, detailed plans have to be made to manufacture the product conform the design decisions and specifications. When the product is delivered to the customer, field data of the performance of the product can be collected. This data then can be used for future reliability improvements. [25]

The mentioned reliability engineering activities during a product development process can be defined in a reliability circle, like Figure 20.

![Figure 20 A reliability circle [25]](image)

### 3.2.1. Reliability measures

The reliability characteristics of hardware and software can be defined and described with various measures. With reliability measures the effectiveness of a system can be defined. The operational requirements must be reflected by the reliability characteristics or measures. The reliability measures can be classified in four classes: [26]

1. **Basic reliability measures**
   - Predicts the system's ability to operate without maintenance and logistic support. Reliability function and failure function are measures in this category.

2. **Mission reliability measures**
   - Predicts the ability of the system to complete its mission. Considers only those failures that cause mission failure. Failure Free Operating Period (FFOP), Maintenance Free Operating Period (MFOP), mission reliability and hazard function are applied in this category.

3. **Operational Reliability Measures**
   - Predicts the performance of the system when in operating conditions combined with the effect of quality, environment, effect of design, maintenance, support policy, etc. In this category Mean Time Between Critical Failure (MTBCF), Mean Time Between Overhaul (MTBO), Maintenance Free Operating Period (MFOP), Mean Time Between Unscheduled Removal (MTBUR) and Mean Time Between Maintenance (MTBM) are applied.

4. **Contractual reliability measures**
Defines, evaluates and measures the manufacturer’s program. The contractual reliability is a combined calculation of the manufacturing characteristics combined with the considered design. Mean Time To Failure (MTTF), Mean Time Between Failure (MTBF) and Failure rate are applied in this category. [26]

**Mean time to failure** is the mean time to (first) failure of a system after service, it’s the average time between failures.

**Mean time between failure** is the average time that a system works without failure. When a component of a system fails, it is replaced, or maintenance activities are applied. When a component is replaced or repaired it has different wear out characteristics in comparison to the other components in the system. Due to the different characteristics between the different components it is hard to predict the mean time between failure. The mean time between failure can be calculated with: [26]

\[
MTBF = \frac{\text{total operating period}}{\text{number of failures during operating period}}
\]

**Failure rate** is defined as ‘the ratio of the number of failures of a given category to a given unit of measure’. [27]

**Maintenance** is defined as: ‘the process of maintaining an item in an operational state by either preventing a transition to a failed state or by restoring it to an operational state following failure.’ [28]

**Maintenance Free Operating Period** (MFOP) is defined by U Dinesh Kumar as ‘The period of operation (...) during which an item will be able to carry out all its assigned missions, without the operator being restricted in any way due to system faults or limitations, with the minimum of maintenance.’ [26] It guarantees a certain operation period without interruption for unscheduled maintenance.

Reliability has influence on the availability of a system. **Availability of a system** is the degree to which a system or component is accessible and operational when required for use, also noted as probability. [24]

The **maintainability of a system** ‘is the probability that a process or a system that has failed will be restored to operation effectiveness within a given time’. [29] The availability of a system is influenced by the maintainability of that system. The better the maintainability of a system, the faster it will be available again. The maintainability can be quantified with **mean time to repair** (MTTR). Mean time to repair is ‘the expected or observed time required to repair a system or component and return it to normal operations’. [24] Maintainability can also be expressed in terms of maintenance frequency factors and maintenance cost. The design characteristic of maintainability is dealing with the economy in performance, safety, accuracy, ease and accuracy of maintenance functions. [26]

The reliability of a conveyor belt system can be quantified by using a reliability number, which is a measure of damage. The reliability number is based on the assessment of the impact of wear and damage on the belt conveyor’s performance. It can be used to determine what actions are needed: do
nothing, repair the system or replace the component(s). An example of a reliability number is the wear index. [30]

### 3.2.2. Reliability interrelationships

If failure of a single component in a system leads to multiple parts becoming unavailable for operating, the two components are considered to be operating in series. This is graphically shown in Figure 21, two parts X and Y are operating in series if failure of either of the parts results in failure of the combination. The combined system is operational only if both part X and part Y are available. An example of this type of failure, is failure of a single component leading to a stop of the conveyor belt system. [31]

![Figure 21 Two parts operating in series](image1)

If failure of a component leads to another component taking over the operations of the failed part, the two components are considered to be operating in parallel, as graphically shown in Figure 22. If for example one idler in a conveyor belt system fails, very often other idlers can handle the load near the failed idler and the conveyor belt system doesn’t have to stop operating. Two parts are considered to be operating in parallel if the combination is considered failed when both parts fail. The combined system is operational if either component is available. [31]

![Figure 22 Two parts operating in parallel](image2)

Very often the components in a system are in a more complex interrelationship-combination of parallel and series, as graphically shown in Figure 23.

![Figure 23 Components both in series and parallel relationship](image3)

### 3.2.3. Failure categories

Failures in a system can be classified in different failure modes, failure modes for mechanical components are classified into three categories:

1. Failures due to operating load
For example, failures due to operating load are tensile-yield strength failures, ultimate tensile strength failures, compressive failures, brittle fracture, failures due to shear loading, failures due to contact stresses, creep failures under long term loading, bending failures, fatigue failures and failures due to cavitation.

2. Failures due to environment
   Failure due to extreme oxidation or corrosive operation environments. Coefficient of expansion of materials and thermal stresses can be the cause of these type failures.

3. Failures due to poor manufacturing quality
   Failures due to casting defects, improper inspection, cracks and defects in manufacturing or heat treatment errors. [25]

3.3. Reliability control for conveyor belt systems

Conveyor belt systems are relatively simple in design, but are difficult to maintain due to the large number of rotating and moving parts. Figure 24 shows that for a typical coal mine the belt conveyor systems (BCS) result in the most breakdown time in comparison to the bucket wheel excavators (BWE) and dumping conveyors. [23]

![Figure 24: Total breakdown time versus machine type in the KWB Konin mine] [33]

A better way to control a conveyor belt system is reliability-based control. To achieve reliability control for a conveyor belt system, faults and failures need to be diagnosed and prognosed, and different maintenance strategies have to be applied at the most suitable moment.

3.3.1. Fault and failure diagnosis

The most common failures in a conveyor belt system will be discussed, as well as different methods and techniques available to diagnose faults and failures in a conveyor belt system.
3.3.1.1. Failure mode and effect analysis (FMEA)

A theoretical method to diagnose faults and failures in a system can be established by applying a Failure Mode and Effect Analysis (FMEA). This analysis considers the probability of failure, the failure modes, the consequence of failure (failure effect) and the probability of detection of failure and tries to answer the questions:

- What are the possible failure modes of a component or subsystem?
- What are the consequences of failure?
- How is failure detected?
- How severe is the consequence of a failure?

The military standard SRD-1629A applies to the following definitions in FMEA:

**Failure mode**, the manner by which a failure is observed. **Failure cause**, the physical or chemical processes, design defects, quality defects, part misapplication or other processes which are the basic reason for failure or which initiate the physical process by which deterioration proceeds to failure.

**Failure effect**, the consequence(s) a failure mode has on the operation, function, or status of an item. Failure effects are classified as **local effect**, **next higher-level effect** and **end effect**.

**Local effect**, the consequence(s) a failure mode has on the operation, function, or status of the specific item being analyzed. The **next higher-level effect**, the consequence(s) a failure mode has on the operation, function, or status of the items in the next higher level of indenture above the indenture level under consideration. And the **end effect**, the consequence(s) a failure mode has on the operation, function, or status of the highest indenture level. [34]

In FMEA known and potential failure modes can be identified. Using data and knowledge of the process or product, each potential failure mode and effect is rated in each of the following three factors:

- Severity: the consequence of the failure when it happens.
- Occurrence: the probability or frequency of the failure occurring.
- Detection: the probability of the failure being detected before the impact of the effect is realized. [35]

These three factors can be combined in the risk priority number (RPN), to rank the priority of the failure modes identified. The risk priority number is calculated with:

\[
\text{risk priority number} = \text{severity} \cdot \text{occurrence} \cdot \text{detection}
\]

In appendix A - FMEA, three tables with the different rankings are noted. Table 9 shows the ranking of severity in FMEA, Table 10 shows the ranking for occurrence of failures and Table 11 shows the ranking of detection of a failure.

Failures in a conveyor belt system can occur in all the subsystems, failures that lead to an immediate stop of the system are the most critical.
3.3.1.2. **Drive unit and pulleys failure**

The gearbox of the drive unit of a conveyor belt system can fail. Inside the gearbox the geared wheels and the bearings can wear out. The geared wheels can lose its teeth or the bearing can get stuck. It is also possible that the electric motor (drive) of the drive unit fails. The brakes in the drive unit can overheat and lose the ability to brake.

It is also possible that one of the drive pulleys fails. A pulley consists of two bearings, a shaft, a shell and a coating. All individual components of the pulley can fail, examples are given in Figure 25.

![Figure 25 Examples of damaged pulleys, left: a damaged coating [23], right: a broken bearing [23]](image)

For the KWB Belchatów coal mine the number of failure per drive unit element was researched. The drive unit elements were categorized in motor, coupling, gearbox and pulley. Figure 26 shows the number of failures per drive unit element. [23]

![Figure 26 Number of failures per drive unit element [23]](image)

The cause of failure of drive unit element type was also researched. Failure in bearing(s) or electrical issues (earth) can lead to motor failure. The cause of failure of the coupling(s) could be a cracked shaft, failure of bearing(s) or a damaged seal. See Figure 27.
The cause of failure of pulleys can be the coating, bearing or a cracked shaft. A worn wheel, bearing, cracked shaft or a damaged seal can lead to failure of the gearbox. Figure 28 shows the number of failure of pulleys and gearboxes, related to the cause of failure for the mine in Belchatów.

Based on the data from Belchatów mine Table 1 was formed to show potential failure, potential effect of failure and the possible cause of failure in a drive unit.

<table>
<thead>
<tr>
<th>Potential failure</th>
<th>Potential effect</th>
<th>Possible cause of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor unable to rotate or to deliver sufficient power</td>
<td>Stop of conveyor belt system</td>
<td>Worn out or stuck bearing(s)</td>
</tr>
<tr>
<td>Coupling not able to transfer power from the motor to the pulley.</td>
<td>Stop of conveyor belt system</td>
<td>Cracked shaft</td>
</tr>
<tr>
<td>Pulley not able to transfer power to the belt</td>
<td>Stop of conveyor belt system</td>
<td>Damaged pulley coating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worn out or stuck bearing(s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cracked shaft</td>
</tr>
</tbody>
</table>
### Potential failure

<table>
<thead>
<tr>
<th>Potential failure</th>
<th>Potential effect</th>
<th>Possible cause of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox not able to transfer power from the motor to the belt</td>
<td>Stop of conveyor belt system</td>
<td>Worn wheel due to broken teeth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worn out or stuck bearing(s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cracked shaft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damaged seal(s)</td>
</tr>
</tbody>
</table>

Table 1 An overview of failures in a drive unit of a conveyor belt system

#### 3.3.1.3. Belt failure

The main belt itself can also get damaged, this is the main and most expensive element (up to 50% of total cost [16]) of the conveyor belt system. A belt transmits longitudinal forces necessary to overcome movement resistance. The conveyor drive also transfers large forces onto the conveyor belt via the motion wheels. The belt is exposed to difficult to predict (over)loads of material. The loads often exceed the maximum allowable load prescribed by the manufacturer of the belt. The result is tensile stress concentration in the belt and the belt breaks up. Damage to the belt may be a result of stresses which occur due to the conveyor’s elements having direct contact with the belt. Belt damage resulting from contact with sharp pieces of the transported material or the movement of material along the belt occurs less frequent. [1] It can be teared, punctured, cut open or damaged by abrasion of top or bottom covers. The joints of the belt are critical, the joints can be glued together, vulcanized or mechanical attached to each other.

Another cause of wear in a conveyor belt system is belt deviation. The center line of the belt deviates from the center line of the conveyor. This causes belt edge wear and premature damage to the belt. Belt deviation can be caused by:

- Large deformation of the belt under load
- Large error of outer roller cylindrical form
- Supporting roller rotation is not flexible which causes uneven stress on both sides of the conveyor belt.
- Parallelism error in the cylindrical axis and roller axis.
- Uneven thickness of the belt due to questionable belt quality. [16]

An example of damage due to belt deviation is given in Figure 29.

![Figure 29 Belt deviation [36]](image)
The belt can also run of due to insufficient belt tension or due to misalignments. It is also possible that the belt won't start to run, due to slip between the belt and the pulley.

Damage to the belt can be categorized in 15 damage types: [30]

1. breadth tear
2. puncture
3. tongue-tear
4. longitudinal tear
5. cut
6. edge damages
7. torn out cable
8. varicose vein
9. blister
10. torn out cover
11. extreme abrasive wear
12. bare cables
13. fire damage
14. shingling
15. delamination of joint

According to Lodewijks, breadth tear, puncture, tongue-tear and longitudinal tear make up for about 85% of all reported damages to the conveyor belt. These four damage types are visualized in Figure 30 till Figure 33.

**Figure 30 Breadth tear [30]**

**Figure 31 Puncture [30]**
Failure can also happen in the steel cables inside the belt. The cables can start to corrode or splice, the cables can internally or externally corrode, see Figure 34. Due to corrosion the wires may break separated by a gap or with their ends still in contact, see figure 22. [17]

Breaking up of the belt can lead to long periods of stopping the conveyor belt. Repairing the belt is complicated and time-consuming. It is often caused by stress concentrations transferred by the (steel)
belt core and immobilizes the conveyor belt system. Break-up of the belt often occurs at the joint because the tensile strength is lower in that region than in the belt itself. [1]

Table 2 gives an overview of the possible failures and effects.

<table>
<thead>
<tr>
<th>Potential failure</th>
<th>Potential effect</th>
<th>Possible cause of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Break of belt</td>
<td>Stop of conveyor belt system</td>
<td>Belt punctures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Belt cut</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Belt tear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrosion in steel cords in belt carcass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Belt deviation</td>
</tr>
<tr>
<td>Belt run-off</td>
<td>Stop of conveyor belt system</td>
<td>Belt deviation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insufficient belt tension</td>
</tr>
<tr>
<td>Belt slippage</td>
<td>Conveyor belt won't start to run</td>
<td>Insufficient belt tension</td>
</tr>
<tr>
<td></td>
<td>Belt catching fire</td>
<td>Damaged pulley coating</td>
</tr>
<tr>
<td></td>
<td>Increased power consumption</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 An overview of failures in a conveyor belt

### 3.3.1.4. Idler failure

Another point of failures can be the idlers, the idlers consist of a shell (possible with a coating), a shaft and a bearing. The idlers are used to support the loaded belt. The manufacturing quality of the idlers directly affects running resistance of the idler and the life of a conveyor belt system. Bearing stiffness can also be insufficient, which makes it difficult to assembly the idlers with accuracy. The flexibility of the running idlers is therefore constrained.

If the resistance needed to rotate the idlers increases, the belt can slip onto the idlers. The rolling friction changes into sliding friction. Values of the drag coefficient may increase up to ten times. The increase of rolling friction can be the result of sealing and lubrication problems. In more severe work environments dust and or dirt can get into a bearing when a bearing is not sealed well. Grease used to lubricate the bearings of the idlers starts to degrade after some time, which also results in an increase of rolling resistance of the idlers. [2]

The side idlers in a troughed conveyor belt system are more subjected to damage because of the different load on each individual idler, see Figure 36. Wear in the bearings will lead to a significant increase of external load for the drive units. The power consumption of the drive units will increase. Damaged idlers can also cut the belt open or start a fire due to slipping of the belt on the damaged idler. [16]
Table 3 shows the potential effect of a failed idler.

<table>
<thead>
<tr>
<th>Potential failure</th>
<th>Potential effect</th>
<th>Possible cause of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idler is not able to rotate</td>
<td>Belt catching fire</td>
<td>Worn out or stuck bearing(s)</td>
</tr>
<tr>
<td></td>
<td>Premature failure of the belt</td>
<td>Broken seal(s)</td>
</tr>
<tr>
<td></td>
<td>Increased power consumption</td>
<td>Cracked shaft</td>
</tr>
<tr>
<td></td>
<td>Belt run off</td>
<td>Damaged shell</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insufficient stiffness of bearing</td>
</tr>
</tbody>
</table>

Table 3 An overview of failures in the idlers of a conveyor belt system

3.3.1.5. **Condition monitoring of conveyor belt systems**

To diagnose the mentioned faults and failures in a conveyor belt system, monitoring systems can be applied. According to Bartelmus, ‘monitoring (supervision, tracking) can be the tracking of a machine’s condition or a machine’s work process, using technical means or without them by means of senses. Symptom is a carrier of information about a machine’s condition, perceived or observed by instruments by a person who makes a diagnosis and indicates a malfunction of the machine.’ [17]

Besides physical quantities to assess a machine’s condition, physical quantities which specify the relative positions of the machine’s assembly need to be monitored. Power consumption can be monitored to avoid exceeding of the permissible loading of machine. This ensures the correct operation of a machine, its own safety and the safety of the machine’s users. Bartelmus distinguishes monitoring:

- for diagnostic purposes
- for machine operation safety purposes
- for machine’s process parameters and its operation [17]

In regard to Barthelmus’s categorizing of monitoring the condition of a conveyor belt system, there is an overall need to incorporate quality control and assurance procedures when using conveyor belt systems. The components of a conveyor belt system can be damaged in many ways, so different techniques are required to monitor the condition of the different components. The monitoring of the
system can be real time or according to a time schedule. [23] To diagnose the system a skill to identify the machine’s malfunctions from symptoms is required. [17]

Mr. Pang made an overview of parameters, components involved and possible sensors and technologies to check the status of the parameter of conveyor belt systems, see Table 4.

<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>Torque meter</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>

Table 4 Parameter, component and sensor/technology to check the status of a conveyor belt system [37]

There is no universal solution for condition monitoring of conveyor belt systems. Depending on the operational condition, material type (i.e. coal, lignite or iron ore), belt type and form of the most frequent degradation processes there might be either a simple and inexpensive solution or a complex and costly one. [38]
Monitoring of the system often occurs with sensors, which can be categorized into fixed and mobile sensors. **Mobile sensors** can be installed for example on an outstretching arm of a maintenance trolley or on the arm of a robot. An advantage of the mobile sensors is the lowering of complexity of the sensor network and infrastructure. However, a disadvantage that the monitoring circle of a mobile sensor can be much longer than the monitoring circle of a fixed sensor. **Fixed sensors** stay in places that are not moving, in most cases this is the frame of the conveyor belt system. [39]

To be able to use the signals from the different sensors, **data acquisition recorders** are used. These devices digitize the various transducer signals and can be recorded on a computer. Up to 50 signals can be recorded simultaneously by a single data acquisition recorder. The recorders can be applied with different sample rates, varying from 0.1 Hz to 10 kHz. The low sampling rates are often used for temperature measurements or weight scale recordings. To adequately capture motor and brake torques, take-up motion, motor contactor response, brake valve and caliper timing and velocity changes high sampling rates are required. [40]

A possible monitoring setup of a conveyor belt system is shown in Figure 37. The belt wear, belt run-off, rate of belt travel and rotational speed of the drum is monitored. Drum slip can be monitored based on the belt velocity and the drum’s rotational speed. Metal elements in the transported material are detected. [17]

![Figure 37 Possible arrangement of devices for monitoring operating parameters and condition of belt conveyor: 1 - impulse sensor, 2 - drum rotational speed monitor, 3 - belt run-off monitor, 4 - metal detector, 5 - belt wear monitor, 6 - rope tension monitor, 7 - belt speed monitor, 8 – belt run-off monitor, 9 – signaling device [17]](image-url)
3.3.1.5.1. Monitoring techniques for belt condition

The monitoring of belt condition is divided in different categories. Some of the mentioned monitoring systems can be used for all categories.

**Belt cover condition**

A vision system can be applied to monitor the condition of the belt cover. Figure 38 shows a possible set-up of such a system. A specialized linear camera acquires images line by line and is send to a computer. Special software enhances the image and tries to find damage (spots) on the belt, see Figure 39 on the right. The software is able to detect a single damage, the type of damage (transversal or longitudinal) and estimate its area size. The detected damages are stored in a database. The software can support the decision-making process for maintenance by means of a statistical analysis, the software can for example provide damage density along the belt length or types of damage. [38]

![Figure 38 Schematic example of a belt cover monitoring system using a vision system](image)

Another way to monitor the condition of the belt cover is by temperature measurements, because it can be an indication of change of material properties and change of condition. Variations in ambient temperature can significantly influence the viscoelastic behaviour of the conveyor belts cover, which is often made out of a rubber compound. In conveyor belt system where elevation changes are significant, temperature measurements are acquired at both the head and tail of the conveyor belt system. In real world, the temperature variations result in deformation of the rubber as it travels over the idlers. This...
results in a change of power consumption of the conveyor belt system. Lower temperatures from optimum can result in idler hearing drag. These temperature measurements can be acquired continuously using a thermocouple and a data acquisition encoder. [40]

**Belt carcass condition**

Conductive monitoring is one of the most popular technologies applied to monitor the belt interior or carcass condition. It can also be applied to monitor belt tension, belt splice, belt tears, belt speed and belt surface. In principle, a conductive monitoring system contains one or more conductors which generate or reflect signals to one or more detectors. The detector receives and transfers the signals to a data acquisition device.

To form an embedded conductive monitoring system, conductors can be embedded into the belt carcass. In this type of embedded monitoring, conductors can be conductor loops, magnets, circuit coils or transponder chips. Detectors can be magnetic sensors, conductive or inductive couplings or powered transmitter/receivers. The detectors are located on the travelling path of the conductors and are placed contactless to the belt, see Figure 40. The detectors receive induced electromotive force signals from the conductors passing through the magnetic or electric fields generated by the detectors. [37]

![Figure 40](image_url)

*Figure 40 Left: principle of embedded conductive monitoring, right: the same principle with example of output [37]*

Figure 41 shows an example of software that monitors a belt with a magnetic module.

![Figure 41](image_url)

*Figure 41 3D image and 2D image of a splice in two belt segments, software colors most critical spots to the color red [42]*
The embedded system can be applied for many different aspects of the conveyor belt system, Pang gave the following options for this system:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identity</td>
<td>Belt splice</td>
</tr>
<tr>
<td></td>
<td>Head and tail of belt splice</td>
</tr>
<tr>
<td></td>
<td>Belt longitudinal position (relates to belt velocity and acceleration)</td>
</tr>
<tr>
<td>Speed</td>
<td>Belt</td>
</tr>
<tr>
<td></td>
<td>Pulley</td>
</tr>
<tr>
<td>Wear</td>
<td>Belt cover</td>
</tr>
<tr>
<td></td>
<td>Belt edges</td>
</tr>
<tr>
<td>Tension</td>
<td>Belt tension during diverse system states (relates to belt overload protection)</td>
</tr>
<tr>
<td></td>
<td>Belt tension at specific position (relates to the tension of special belt splice)</td>
</tr>
<tr>
<td>Transverse position</td>
<td>Belt position (relates to conveyor belt system structure, side guide rolls, idler rolls and pulleys, belt run off, misalignment and danger of belt hitting the structure.)</td>
</tr>
<tr>
<td>Vibration</td>
<td>Belt (belt horizontal position relates to detect belt lift off)</td>
</tr>
</tbody>
</table>

*Table 5 Opportunities of the embedded conductive system [37]*

In other applications, the conductive monitoring system only has detectors which receive the transmitted signals from the monitored objects themselves. An early application of this technique in belt monitoring was charging the steel cables inside the belt by applying transducers that generate a magnetic field, see Figure 42. To indicate the condition of the steel cord the distortion of the magnetic field can be detected by measuring the electrical field transmitted by the steel cables. In this application, the steel cords are magnetized and the induced electromotive force that is generated by the magnetic field at the breaks, cord ends or damaged areas is measured. Changes in the steel cords or imperfections will lead to change of the magnetic field. Measuring and recording magnetic field disturbances can be used to indicate the presence of corrosion, cord damage, cord breaks, splice rip or the presence of a splice. [37]

![Figure 42 Schematic view of steel cord monitoring](image)

*Figure 42 Schematic view of steel cord monitoring [43]*
An example of the disturbance in the magnetic field due to damage in the steel cords of the conveyor belt is given in Figure 43.

![Figure 43 Change of magnetic field due to broken steel cords][23]

It is also possible to combine the images of the visual monitoring system with the information of changes in the magnetic field in the belt, see Figure 44. For this purpose, the two modules (visual and magnetic field monitoring systems) were synchronized by Blazej, to obtain a 2D image of the belt. [44]

With this technique both the belt cover as well as damage to the carcass can be visualized.

![Figure 44 Synchronized measurement results for vision module (bottom) and magnetic module (top) for belt core and cover (red)][44]

The condition of the belt can also be monitored using an infrared thermography system. This procedure involves acquiring infrared images of the belt and their processing. To detect damages in the top cover of the belt as well as damage in the steel cords inside the belt. The change of condition will modify the distribution of dispersed energy related to the internal friction, bending resistance etc. The energy that is transformed into heat can be detected with infrared thermography. An example of a thermal image of steel cord damage inside a is given in Figure 45. [38]
The acquired images are often difficult to interpret. The automation of understanding the images and applying decision making on these images requires advanced processing. Figure 46 shows on the left from top to bottom the uniform temperature distribution of a non-damaged belt, to a damaged belt and on the right the time series corresponding to the segmented images. [38]

Another example of monitoring the condition of the belt without destruction, is applying metrotomography. Its principle is based on the use of X-rays. The property of the X-ray easily going through a solid material is used for this technique. The intensity of radiation is decreasing behind an object that is analyzed. The decrease of intensity is due to the absorption properties of a material and the cumulated thickness through which the X-rays have to go. The change of intensity can detect defects in the analyzed object.

Metrotomography of conveyor belt samples brings some advantages in comparison to conventional measuring and analyzing methods. An advantage of metrotomography is that non-accessible places in a conveyor belt can now be visualized. Computer tomography can make a virtual model, which can be analyzed in cross sections and can be virtually rotated. By digitalizing the measured conveyor belt sample by tomography, every point of the surface as well as the inside of the object is obtained. Software creates a three-dimensional model of the analyzed sample in the form of a cloud of points. The points are ordered in space and contain information about the absorptive property of the sample in that position. These points are called voxels, which is derived from volume pixel. The information is
shown in shades of gray color in a virtual environment. An example of cross section image gained with metrotomography technology is given in Figure 47 and Figure 48.

![Figure 47 Image of a cross section of a conveyor belt gained with metrotomography [45]](image1)

Figure 47 Image of a cross section of a conveyor belt gained with metrotomography [45]

![Figure 48 Image acquired with metrotomography technology of a textile layered conveyor belt [45]](image2)

Figure 48 Image acquired with metrotomography technology of a textile layered conveyor belt [45]

Porosity checks or detection of foreign materials inside an object can be visualized with great ease with metrotomography, as seen in Figure 49. With high precision the porosity of a material, the location, the size and shape of every bubble that got into the material during manufacturing can be determined. [45]

![Figure 49 Section view of a conveyor belt sample acquired with metrotomography technology [45]](image3)

Figure 49 Section view of a conveyor belt sample acquired with metrotomography technology [45]

Software makes it possible to monitor dimensional changes in the material. Mainly in the rubber structure, in the textile layer, material faults and homogeneities, etc. In Figure 49 the homogeneity can
be identified. The quality of the material of conveyor belt can be checked, which is important for the determination of conveyor belt using. [45]

**Belt joint condition**
The belt joints can be monitored by placing some magnetic field sources in a joint area and measuring the distance between the magnetic field sources. This way elongation of the belt can be monitored. Cut of the belt cover can be detected using an electromagnetic field transmitter. If the belt is cut, the electric circuit will cut-off and the transmitter will stop working.

**Belt splice condition**
Conductive monitoring can also be used to monitor the belt splice condition. [46] Two transponder chips are located in front and after the splice region, see Figure 50. An external transmitter/receiver unit receives signals from the transponder chips, which can monitor the spacing of the two transponder chips. The monitoring of the spacing between the chips is based on time dependent spacing of the two signals. If spacing $S$ of the transponder chips exceeds a predefined $S_{ref}$, the external transmitter/receiver unit knows if the spacing is exceeding a critical change in length. [37]

*Figure 50 Schematic view of a belt splice monitoring system [37]*

**Belt thickness**
To determine belt thickness non-destructive tests can be applied, like ultrasonic measurements. This system is able to measure thickness of a thin, very thick or multi-layer material by means of single element transducers. Fedorko applied this technique in transversal direction of the conveyor belt. He marked 65 measuring points in a distance of 20 mm from each other, where the first and the last measuring point was located on the edge of the belt. An example of measured values of thickness of individual layers are in shown in Figure 51. [45]

*Figure 51 Cross section of NF 630/3 6 +2 conveyor belt changed due to dynamic wear [45]*
From these measured values, wear of the lower and upper covering layer can be determined and visualized, as show in Figure 52 and Figure 53.

**Figure 52 Wear in the lower covering layer of NF 630/3 6 + 2 conveyor belt [45]**

**Figure 53 Wear in the upper covering layer of NF 630/3 6 + 2 conveyor belt [45]**

**Belt speed**

To confirm that the conveyor belt system is operating at its design speed, monitoring of the belt speed is essential. It is also important to verify the starting and stopping dynamics of the total conveyor belt system. Two of the most popular methods for determining the velocity of the conveyor belt, are either an optical encoder or a magnetic pickup sensor. [40]

A measuring system with an optical encoder uses a transparent disk with a pattern of opaque segments on one of its surfaces. The opaque segments interrupt a light beam from a light source and prevent the illumination of a light sensor (or reflect a light beam to illuminate a light sensor sided with the light
source). Binary outputs of ‘0’ and ‘1’ are produced when the opaque segments pass through the light sensor. [37] Figure 54 shows the principle of an optical encoder.

![Figure 54 Principle of an optical encoder [37]](image)

In a measuring system with a magnetic encoder, a nonmagnetic disk is applied with a pattern consisting of magnetized segments on one of its surfaces. Above the segments a ferromagnetic core is placed, this core has an input winding and an output winding. The magnetic segments passing through the core give a binary output of ‘0’ and ‘1’. [37] Figure 55 shows the principle of a magnetic encoder.

![Figure 55 Principle of a magnetic encoder [37]](image)

In a conveyor belt system with angular encoders, the speed can be measured with a contacting method. An encoder is mechanically attached or linked to the monitored object. A typical example of this method is to run a rotating sensing device (a wheel) of an angular encoder directly on the belt. The count of rotations of the wheel over time results in the belt speed. [37] Figure 56 shows an example of a rotating sensing device.

![Figure 56 A tachometer on a belt for belt speed monitoring [37]](image)
**Belt slippage**

In a conveyor belt system, two velocity encoder units can be used to measure possible belt slippage. One unit is mounted on the pulley assembly to measure the angular speed of the pulley. Another unit is placed on the belt itself and measures the actual angular belt speed. Any velocity difference between these two can indicate belt slip. [40]

**Belt tension**

To measure the tension in the belt, load cells can be applied. Load cells are often placed in the cable arrangement of the take-up system, to measure the take-up tension. It is also possible to place a load cell in the belt supporting idlers to monitor the belt load. [37] If possible, a calibrated load cell is used, the error made in the tension measurement is less than 1%. The take-up structure can also be strain-gauged to be used as a load cell. [40]

**Belt take up displacement**

Take-up displacement is measured to verify the take-up displacement requirements and its theoretical prediction. Measurement of the belt take up displacement happens with the same equipment used for measuring the conveyor speed. In this case however, the pulses are not converted to speed, but to displacements.

**Belt misalignment**

Due to misalignment the belt can run into the structure, the belt and the rollers can get damaged and material can get spoiled. To prevent this, it is important to monitor the alignment of the belt. By means of belt alignment switches the transverse position of the belt can be monitored. An example is given in Figure 57.

![Figure 57 An example of a conveyor belt misalignment switch](image)

The alignment unit is often applied in a pair of on/off switches, one on each side of the belt where misalignment is likely to occur. If the belt touches one of the on/off switches and exceeds a certain limit, the conveyor belt system can be stopped or slowed down. Damage to the belt and associated rollers can be prevented this way.
Another way to track belt misalignment is by applying a belt tracking roller, this roller can detect and respond to belt misalignment instantly. An example of such a belt tracking roller is given in Figure 58 and is made by Rulmeca in Italy.

![Figure 58 A belt tracking roller](image)

3.3.1.5.2. Monitoring techniques for drive unit, brakes, pulleys and idlers

For pulleys, idlers and gearboxes (bearings and geared wheels) a vibration-based condition monitoring system can be of help. [17] To monitor the condition of the drive unit the power and torque can be monitored. Temperature based measurements can show the condition of the bearings, brakes, pulleys and idlers. [23]

Monitoring system vibrations

Vibration in a component occurs when it oscillates about its equilibrium points. In a conveyor belt system this can be the rotation of bearings in idlers rollers, pulley rotation, fluctuation of the belt surface, unbalance in components, misalignment of the belt and other rotating parts in the drive system. The operational status of these parts can be monitored by detecting vibrations. Vibrations can create sound, which are acoustic waves travelling through the air. Acoustic sensors can be applied to measure these signals. By sound or vibration analyses the measured complex wave fronts need to be identified. Fourier transform or Laplace transform can mathematically convert the signals to the frequency domain. The most common method to gain the magnitude in decibels (dB) and the associated radian of the frequency components in the signals is the Fourier transform. [37]

The relation between machine condition and intensity of the vibration signals can be distinguished in the spectral frequency ranges. To assess a system based on vibrations, the components must be detected in the frequency spectrum before the system comes in to operation and the hazard must be determined. An example of the identification of components (the drive shaft, gearing and bearings in the drive unit of a conveyor belt system) based on frequencies is given in Figure 59. One of the symptoms indicating change in condition is the rapidly increasing of vibrations up to a certain limit. [17]
Another way to monitor the vibrations in a system is by means of measuring the accelerations in the system with accelerometers. [49] It is also possible to monitor changes of the distance between magnets and a sensor that cause changes in strength of the magnetic field to indicate vibrations. An example of this system is shown in Figure 60.

In condition monitoring of conveyor belt systems, the vibration magnitudes of the different components are recorded in the early stage of its life. At periodic intervals during its life the vibration is monitored again. If magnitudes of the vibrations are different from the measurements in early stage of life, change in component condition can be indicated. [37]

Figure 61 shows the trend of condition change based on measuring the vibrations in a system. In the running in phase of the system, the vibrations start to decline, but in operation the vibrations start to increase over time. At intensive wear the vibrations rapidly increase. In case of external pollution, intensive wear of roller bearings occurs. This leads to a rapid increase in the level of vibrations. In areas of instability the increase may be abrupt. [17]
Figure 61 Trend of condition change measured in accelerations [m/s²], a - running-in, b - normal operation, c - intensive wear [17]

Monitoring power and torque

To check the accuracy of the design and if a sufficient amount of power is installed, power and torque measurements can be done. According to Lodewijks there are three common methods for measuring conveyor power at the drive pulley: [40]

1. Power transducers

   The current and voltage going into the drive system is measured and is converted to motor power. This way of measuring includes all electrical and mechanical losses in the drive unit. A guess must be made for the energy loss of each individual component to find the actual power consumed by the conveyor belt itself.

2. Measure motor RPM

   The measured rotational speed of the motor is combined with the motor slip power curve. This method includes the losses in the total drive unit, like the fluid couplings, gearbox and other intermediate equipment. It cannot directly determine the conveyor power at the output shaft of the drive unit.

3. Measure the strain in the drive pulley shaft

   The deformation of the drive pulley shaft directly converts to the torque of the drive. The torque is measured by applying four strain gauges on the motor shaft or the pulley, to form a Wheatstone bridge circuit. The electrical resistances in the Wheatstone bridge changes when the shaft deforms due to braking or acceleration of the shaft. The unbalances in resistance result in an out-of-balance output, which relates to the stress acting on the shaft. This stress can be converted to a torque value. [37]

To obtain the conveyor power, the torque is multiplied by the conveyor’s velocity and divided by the pulley’s radius. Wires cannot be directly connected to the gauges due to the shaft’s rotation, so wireless methods are often applied. On the rotating shaft a small battery powered transmitter and transmitting antenna is placed. A receiving antenna is connected to a receiver unit, which converts the radio signal to a DC voltage. The data acquisition recorder acquires the signal as voltage. Figure 62 shows an example of this measurement system.
The brake torque can be monitored with strain gauges as well, as shown in figure 43.

Monitoring of rotational resistance

By measuring the rotational resistance of the idlers in the conveyor belt system wear can be identified. This was applied by Robert Król, with a measuring bolt, on which a set of foil strain gauges is glued that react on shearing forces. The rotational resistance is calculated by means of the relationship between the moment transmitted to the idlers and the measured shearing forces. The measuring bolts can be mounted on the openings of the idlers axle. [50]

A test setup for the monitoring of rotational resistance is given in Figure 64. This technique is not used in the operational field of the conveyor belt system yet, it is only used in the laboratory environment at the moment.

Figure 62 An example of strain gauges placed on the drive unit [40]

Figure 63 Brake torque monitoring system [40]

Figure 64 Test setup for measuring loaded idler rotational resistance: 1 - bracket, 2 - load exerting wheel, 3 – drive mechanism, 4 – set screw, 5 – measuring bolt [50]
The technique based on rotational resistance can provide useful information about the condition of the idlers. The measured rotational resistance in new idlers are smaller than the measured rotational resistance in used idlers, as shown in Figure 65. The increase of rotational resistance is a measure of the condition of the idlers, based on these measurements actions can be taken to apply maintenance on the idlers.

![Figure 65 Rotational resistance to motion of new and used idlers as a function of radial loading [50]](image)

**Monitoring of temperature**

The temperature of elements or the temperature distribution can be monitored with a contact or noncontact method. For contact monitoring it is necessary to install a temperature sensor in a place where the temperature will be representative for the condition of the component or to use a portable temperature gauge.

To determine the temperature distribution thermography can be applied. As the conveyor belt system starts to run, the different components emit heat in the form of visible- and invisible-range waves. The invisible heat radiation is called infrared radiation. The temperature distribution monitored by thermographic devices is displayed in the form of a two-dimensional color image. [17] With this application the temperature of the gearbox, motor, bearings and couplings can be monitored as well as the drive pulley.

An example of temperature monitoring is the increased temperature distributions near the bearings in idlers, as indication of wear or damage. Bartelmus did tests with this type of assessment on 10.000 idler runners. The increase in temperature above the ambient temperature and the temperature trend were determined. He concluded that a rise of 5º Celsius over the ambient temperature, the idler shows a tendency towards a change in its condition and it should be replaced after three weeks. When the temperature rises more than 15º Celsius above the ambient temperature, the runner is unrepairable. [17] Figure 66 graphically shows the temperature increase of idlers.
1 Rise in temperature above ambient temperature [Celsius].
2 Rise in temperature for runner in suitable condition.
3 Rise in runner temperature caused by change in condition – runner can be repaired.
4 Rise in runner temperature caused by change in condition – runner cannot be restored to its original condition.
5 Failure condition temperature range.
6 Number of weeks [-].

Another way of monitoring the condition of the system is by applying a distributed temperature sensing (DTS) system. This system uses optical fiber technology and is a safe method that can be utilized in underground mine operations. The system can continuously measure and monitor the temperature variation of the rolling components on a conveyor belt system, to identify any mechanical failures. The DTS system is comprised of a DTS unit and a fiber optic cable. The fiber optic cable used to transmit data and is also capable to sense temperatures. The DTS system can provide a continuous temperature distribution profile along the entire length of fiber optic cable with high accuracy. [51]

A new development of the TU Delft is the smart idler roll with embedded sensor node. With these idler rollers a group of conveyor idlers can be monitored by means of RFID sensor nodes. One sensor node is composed of an active RFID tag and is combined with a temperature sensor. The temperature sensor can provide information about the condition of the idler.

The idler is still under development and the sensor inside the idler is currently powered by a 3,6 volt lithium battery and embedded into the idler roll shaft, see Figure 67.

A completely closed metal environment would block any signal from the RFID sensor node. To solve this issue, at the end of the shaft a plastic cover is placed to enclose the antenna of the RFID tag. This way a signal outside the shaft can be provided. The plastic cover also protects the antenna from the harsh environment where the conveyor belt is placed. [52]

Figure 66 Temperature monitoring of idlers [17]

Figure 67 Idler roll with embedded sensor node [52]
### An overview of monitoring techniques and applications

Table 6 presents an overview of the components of a conveyor belt system that are most influenced by wear and tear. The sensor technologies to monitor the component are mentioned as well.

<table>
<thead>
<tr>
<th>Monitored component of a conveyor belt system</th>
<th>Subassembly or specific characteristic</th>
<th>Measured property</th>
<th>Possible sensor technology</th>
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<td>Rotational resistance</td>
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</table>

*Table 6 An overview of components to monitor with accompanying sensor technologies*

### 3.3.1.5.4. Monitoring by human inspection

Besides all the mentioned monitoring systems, the condition of the belt is often assessed visually by experienced maintenance workers. These workers use their eyes and ears to see and hear if the components are still operating in the desired way, see Figure 68 on the left. They decide if immediate maintenance is needed or when maintenance should be performed.
On long conveyor belt systems special carriages are available that can travel over the conveyor belt system, so the inspector(s) can move over the belt to inspect it. An example of such a carriage is given on the right in Figure 68. Structural health monitoring can also be applied during operation of the conveyor belt system, to monitor and assess the condition of the system. Sensing hardware with advanced signal processing software can be integrated into the system, making non-destructive testing become an integral part of the system. By monitoring the health of the system, the effects of loads on damage such as fatigue propagating through the system during operation can be monitored and addressed. [55]

During operation different parameters can be assessed to check the condition of the conveyor belt system. The assessment of a conveyor belt system in operational mode can be continuous, interval based or incidental. The data from the measurement equipment can be transmitted to a central monitoring system that can assess the condition of the conveyor belt system. The transfer of data can be applied with radio frequency (RFID) technology, WiFi technology or by means of a wired system. [56]

3.3.2. Fault and failure prognosis

There are different methods to prognose faults and failures in a system, for example the reliability block diagram, fault trees, event trees, Markov chain and Monte Carlo simulation analysis. These methods will be discussed.

3.3.2.1. Reliability block diagram (RBD)

A reliability block diagram is an event diagram used to answer the question: ‘Which elements of the item under consideration are necessary for the fulfilment of the required function and which can fail without affecting it?’ [57] The elements that are required for the function of the product are connected in series, elements which can fail without effect on the required function are parallel connected. This
block diagram helps to understand which parts and components in the system are critical for operation of the system.

By means of a failure mode and effect analysis the effect of failure of all individual elements is verified. The reliability block diagram is derived top down for large systems as shown in Figure 69. At each level, the corresponding required function is derived from that at the next higher level.

![Reliability block diagram for a 4-level system](image)

Figure 69 Reliability block diagram for a 4-level system [57]

### 3.3.2.2. Fault tree analysis (FTA)

Fault tree analysis is a failure oriented, deductive and top-down approach, which considers an undesirable event associated with the system as the top event, the various possible combinations of fault events leading to the top event are represented with logic gates. Fault tree is a qualitative model which provides useful information on the various causes of undesired top events.

The faults can be events that are associated with component hardware failure, software error, human errors or any other relevant events which can lead to top events. The gates show the relationships of faults (or events) needed for the occurrence of a higher event. The gates those serve to permit or inhibit the fault logic up the tree. The gate symbol denotes the type of relationship of the input (lower) events required for the output (higher) event. [25] An example of a fault tree is given in Figure 70.
3.3.2.3. Event tree analysis (ETA)

Event tree analysis is an inductive method which shows all possible outcomes resulting from an initiating event. Initiating event can be sub system failure or external event (for example flood, fire or earthquake) or operator error. Event tree models the sequences containing relationships among initiating event and subsequent responses along with the end states. The subsequence responses events (branches of event tree) are safety systems or also known as pivotal events. Various accident sequences are identified and probability of occurrence of each sequence is further quantified. [25] An example of a fault tree is given in Figure 71.

![Fault tree diagram](image)

**Figure 70** An example of a fault tree for a car hitting an object [58]

![Event tree diagram](image)

**Figure 71** An example of an event tree with three safety systems (SS) [25]
3.3.2.4. Progressive reliability method (PRM)

The progressive reliability method is a method to quantify the system reliability using the basic rules of the probability theory. This general method can compute the probability of system failure in terms of its performance and functionality or the failure of certain system components.

In the progressive reliability method, the reliability assessment accounts for the possible progressive failures of the components until the system failure criterion is met. Such assessment requires calculating the probability of various failure scenarios and calculating the probability of system failure under each scenario. After failure of a component, the probability space of the remaining components changes due to the redistribution of the demands. Any damaged state of the system may occur through multiple failure scenarios. With this method a general solution that accounts for all such complexities is developed.

In this method, two important terminologies are essential and frequently referred to: the configuration and the failure scenario. The configuration is defined as any possible state of the structure in terms of the possible state (failure or no failure) of its components. The failure scenario is defined as the steps that lead from the intact configuration to a failed configuration.

The progressive reliability method was used for offshore mooring systems by Mousavi [59] and is graphically shown in Figure 72. Here the conditional probabilities of configurations are calculated in the structure. \( \{ \tilde{X}_0^{(1)}, \tilde{X}_1^{(1)}, \tilde{X}_2^{(1)}, \tilde{X}_3^{(1)}, \tilde{X}_3^{(2)} \} \) are possible failure configurations.

![Figure 72 The conditional probabilities of configurations calculated [59]](image)

3.3.2.5. Bayesian network

Bayesian theory describes the probability of a future event, based on prior knowledge of conditions related to the event. The Bayesian theorem is mathematically defined as:

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

With \( P(A) \) and \( P(B) \) the probabilities of A and B independent of each other. \( P(A|B) \) is the likelihood of event A occurring given that B is true, \( P(B|A) \) is the likelihood of event B occurring given that A is true. [60]
A Bayesian network is based on the Bayesian theory and can be used to identify the cause of an event or to determine the effect of an event. At the nodes in the network the probabilistic functions are placed and are connected to show the relationships. [61]

A simple Bayesian network is shown in Figure 73 for the measurement of the health of a bearing. The 'vibrations' node represents whether vibration is measured or not and the 'oil pressure' node represents the oil pressure measurement. Each node is accompanied with a conditional probability table, which defines the probability of a good or worn out bearing in combination with the measurements.

![Bayesian Network Diagram](image)

*Figure 73 A simple Bayesian network for the measurement of the health of a bearing [62]*

### 3.3.2.6. Markov models

Markov models provide improved modeling of systems where one or more conditions such as strong dependencies between components, repairable components, coverage factors (failures detected or not detected), multiple states etc. are present. The size of the Markov model explodes for large systems, hence it is practical to combine this technique with fault tree analysis.

The Markov model evaluates the probability of jumping from one known state into the next logical state until the system has reached the final or totally failed state. [63]

A simple Markov model example is given for the behavior of a dog going from one state to another state. The state space, the initial probabilities and the transition probabilities have to be defined. The state space is defined as sleeping, eating or pooping, with initial probabilities of 35%, 35% and 30% respectively. The transition probabilities are defined in Table 7. [64]

<table>
<thead>
<tr>
<th>State</th>
<th>Sleeping</th>
<th>Eating</th>
<th>Pooping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping</td>
<td>0,4</td>
<td>0,2</td>
<td>0,4</td>
</tr>
<tr>
<td>Eating</td>
<td>0,45</td>
<td>0,45</td>
<td>0,1</td>
</tr>
<tr>
<td>Pooping</td>
<td>0,45</td>
<td>0,25</td>
<td>0,3</td>
</tr>
</tbody>
</table>

*Table 7 Transition probabilities from one state to the next one [64]*

Graphically the Markov model is shown in Figure 74, which shows the transition probabilities from each state to the next state. For this case it is the behavior of a dog, but it can also be applied for failure of components in a conveyor belt system.
3.3.2.7. Monte Carlo simulation

In Monte Carlo simulation, random failure and repair times from each components failure and repair distribution are generated. These failure and repair times are then combined in accordance with the way the components are reliability-wise arranged within a system. The overall results are analyzed in order to determine the behavior of the entire system.

Understanding of the system behavior is essential for system success and failure logic. It is assumed that the reliability values for the components have been determined using standard (or accelerated) life data analysis techniques, so that the reliability function for each component is known. With this component level reliability information available, simulation can then be performed to determine the reliability of the entire system. The random failure or repair times of components is obtained using uniform random numbers and converting these into required density function as per the component probability density function. [25]

3.3.2.8. Finite element method (FEM)

The stresses on the components also must be determined and assessed before production. By means of a finite element method the behavior of components under stress loads can be determined.

An example of a finite element method analysis is given in Figure 75. With this type of analysis, the deformations, fatigue or (contact) pressures (Figure 76) of components can be simulated with software. The deformations in the different materials should stay within the elastic zone of the material.

Figure 74 A simple Markov model for the behavior of a dog [64]

Figure 75 Example of FEM analysis on a conveyor belt system showing deformations [mm] [65]
3.3.2.9. **Discrete element method (DEM)**

With discrete element software it is possible to simulate the behavior of particles in a conveyor belt system. This way the design can be verified to operational requirements and possible wear spots can be noticed. An example of a discrete element simulation is shown in Figure 77.

![Figure 77 Particles moving from a chute on to a conveyor belt system](image)

**Figure 77** Particles moving from a chute on to a conveyor belt system [66]

3.3.2.10. **Destructive testing**

Besides non-destructive testing, it is also possible to assess components of the conveyor belt system with destructive tests. For example, to assess if the chosen belt can withstand the designed material impact and so the ability of the conveyor belt to absorb the impact energy by the deformation work without destruction of it. When the impact energy is greater than the absorption ability of the conveyor belt, damage to the belt will occur. This damage is visible on the upper belt cover, mostly in the form of transversal and longitudinal grooves and cracks or punctures.

To assess the quality of the conveyor belt samples of new, worn and renovated conveyor belts can be tested with a test device showed in Figure 78 on the left. By means of this test device the stroke of material onto a conveyor belt can be simulated. Two types of impactors where used, as shown in Figure
78 on the right. The pyramidal shape impactor simulates the impact of a sharp material with hard edges, the spherical impactor simulates an inconsistent, crumbly material. [67]

![Diagram of test device with drop hammer and impactor details]

*Figure 78* Left: test device with drop hammer, right: impactor details [67]

Four degrees of damage were identified by Andrejiova et al., the first degree is 'without damage', the second degree 'partial damage of cover layers', the third degree 'total damage of upper cover and inner structure' and the fourth degree 'puncture'. The individual types of damage were divided into two categories: 'insignificant damage' and 'significant damage'. The significant damage classifies damage that leads to a total failure of the conveyor belt. Degrees of damage, coupled to the type of conveyor belt, type of impactor and impact height are given in figure 54.

![Graph showing occurrence of damages during experiments]

*Figure 79* Occurrence of damages during experiments [67]
By means of this method the conveyor belt most suitable for the type of material that is desired to use in the conveyor belt system can be chosen. Conveyor belt samples can also be tested after some operation time to verify if the belt is still in good condition.

### 3.3.3. Capital expenditures

Investments need to be done to buy a conveyor belt system. The capital expenditure considers cost of mechanical, electrical, civil, structural and instrumentation equipment. There might be a cost for modifications of existing equipment, which may be required to incorporate the new conveyor belt system. There will be a cost to install, commission and test the conveyor belt system as well. [68]

Six main contributors to the investment may be distinguished in conveyor belt systems:

1. The idlers
2. The conveyor belt
3. The drive unit
4. Pulleys
5. The support structure of the conveyor belt system
6. Electrical equipment

For a conventional 1.5 meter wide and 500-meter-long conveyor belt, operating at a speed of 4 m/s, a capacity of 4.800 tons/hour and 5 drive units, Arora and Shinde made the breakup of capital cost as shown in Figure 80.

![Figure 80 Breakup of capital cost for a specific conveyor belt system [69]](image)

The belt, idlers and the electrical equipment are the three most expensive parts of the conveyor belt system.

A reliability-based control system will add more cost to the investment. According to Blazej [70] the simplest monitoring equipment for only the belt without the ability to measure cover thickness or without cut preventing options, starts around €35.000. These systems don’t offer automatic evaluation of the
belt condition, a human operator must assess the condition. A reliability-based control system only based on the belt condition, will be more expensive.

### 3.3.4. Maintenance

Generally, maintenance on conveyor belt systems can be divided in condition monitoring or inspection of the total system and servicing of its components. Condition monitoring is the periodic or continuous interpretation and measurement of data to indicate the condition of the component. It helps to determine the need for servicing or replacement. Condition monitoring acquires data from sensors, with different assessment methods the data can be interpreted, and corrective actions can be done on components that are going to fail. It is preventing fail systems from developing and propagating.

The concept of condition monitoring is to identify subtle operation changes, like increased vibration levels. This can be an indication of the developing of an electrical or mechanical problem. Identification of these problems in an early stage provide more time to plan for repair or machine downtime. [54]

The condition of a component starts to decrease over time, as shown in Figure 81. The potential of failure or function failure is increasing.

![Figure 81 Potential failure (P) and functional failure (F) [26]](image)

To develop a maintenance model or strategy for a system the most frequently used criteria are:

1. Minimizing of maintenance cost, down time and time to repair.
2. Maximizing of revenue, profit, time between failure and availability.
3. Achieving the required level of reliability and safety. [26]

#### 3.3.4.1. Maintenance cost

In common, with increasing potential of failure, the cost and downtime due to repairs start to increase. Figure 82 shows the deterioration impact on the cost and downtime for equipment used in the mining industry, this equipment includes conveyor belt systems.
Figure 82 Deterioration impact on the cost and downtime due to repair of equipment used in mining industries [71]

Unplanned downtime of a conveyor belt system comes with great losses. According to Wipro for a conveyor belt system applied in coal mining industries with a capacity of 1.000 to 3.500 tons/hour of coal, the losses are around €375 to €1.250 per minute. [72]

The maintenance of equipment has a significant impact on the total operating cost of a system. A lot of indirect costs can be solved with proper maintenance. [73] These costs can be illustrated with an iceberg model for maintenance as shown in Figure 83. An example of an indirect cost in a conveyor belt system is the increase of power consumption of the drive unit due to wear in the bearings of the drive unit. By replacing or repairing the bearings, the power consumption will decrease and so do the operational costs.

The total production cost of a conveyor belt system related to the daily production of a mine was researched by Bagherpour [74] and is shown in Figure 84. He noted that the total production cost of a conveyor belt system drops when the system is applied for higher production rates. This is the result of reduced operating cost and reduced capital cost (investment of equipment).
The operational costs of a conveyor belt system were divided by Nel [75] in power, idler, belt replacement and drives. He researched the contribution of the individual components to the total operational cost of a conveyor belt system, as seen in Figure 85.

As can be seen the power consumption of the conveyor belt system pays the largest contribution to the operational cost of the system, followed by the replacement of the conveyor belt. So the conveyor belt should be replaced as least as possible and parts should be running with the least resistance to keep the operational cost low.

The exact maintenance cost of a conveyor belt system is unique for each application and depends on a lot of different factors. The cost is for example depending on the cost of personnel and equipment required to maintain the system, the cost of spare parts, the number of components of the system, the type and abrasiveness of material the system needs to convey, the daily operating hours and the reliability of the different components.
Thieme did a case study to the maintenance cost of idler replacement of conveyor belt systems in three companies. [68]

1. The first company was Europees Massagoed Overlslagbedrijf (EMO) in Rotterdam. Here a maintenance budget of €13.5 million was available for 2013, to a turnover of €149 million. So around 9.1% of total turnover was used for maintenance activities. Around 80 separate conveyor belts are applied with a total combined length of 25 kilometers. Herein an external cost of full-time four men team accounts for €300.000 per year. For the long and critical conveyor belt systems a budget for material and service maintenance is held for €150.000 each, of which €6.000 is spent on new idlers. This means that the material cost for the idlers account for around 4% of the total maintenance cost of the conveyor belt system.

2. The second company was the OBA Bulk Terminal in Amsterdam. Here a conveyor belt system is applied with a total length of 17 kilometers, with approximately 80.000 idlers. Around 10% of the idlers are replaced each year, with an average lifespan of 10 to 15 years. Direct costs of idler replacement were estimated on €250 per idler, which accounts for roughly 10% of the total conveyor maintenance budget.

3. The last company was Queensland Gold Mine in Queensland, Australia. Here four conveyor belt systems are applied, with individual lengths varying from 50 to 100 meters. All maintenance activities are fully manual, a single idler replacement will take around 20 minutes. Maintenance cost for the idlers is estimated at around 10% of their total maintenance budget, which is around €10.000. The material costs of the idlers are less than the labor cost of replacement.

The increased reliability of the system will result in less or less unplanned maintenance activities on the conveyor belt system, but the capital expenditure will increase. This results in less downtime and lowered maintenance costs. For the increased reliability, equipment and decision-making systems are needed. These reliability control systems come at a cost. The owner of the conveyor belt system must find a balance between the cost for the reliability control equipment and the reduced maintenance costs due to the chosen control system.

3.3.4.2. Maintenance strategies

Maintenance is categorized by Lodewijks in four categories: [54]

1. Preventive maintenance

   Calendar based or scheduled maintenance, maintenance activities are planned at certain time intervals or on working hours. It may be based on observed deterioration of components. Preventive jobs are done to prevent breakdown or malfunctions of the system. The maintenance can consist of adjustments, tests, replacement of components, cleaning and measurements.

   In preventive maintenance it is assumed that all equipment will degrade within a time frame typical of their specific classification. The maintenance interval is based on a bathtub curved behavior of a component, which indicates the mean time to failure, as shown in Figure 86. When a component of machine is new (in the break in or start-up phase of the system) failure rate tend to be high.
When the system is in normal operational mode the failure rate is low. When the equipment starts to wear out at the end of its operational life, the failure rate starts to increase again.

Figure 86 Typical bathtub curve, showing failure rate behavior of machinery in relation to lifetime [76]

This type of maintenance has the disadvantage that the mean time between failure for the same component can be different when placed in different types of environments. For example, a bearing in a dusty environment will wear faster than the same bearing in a dust-free environment. [76]

An example of preventive maintenance can be found in the open mine of Kuzbass, where the mining equipment (including conveyor belt systems) are maintained in a preventive way. Maintenance frequency is fixed according to a predefined lifetime of components. Components with the same expectation of lifetime are replaced or repaired as a group. The group of components is replaced based on operating time and not based on the actual condition of the components. [77]

2. Random maintenance

In opportunity based maintenance, repairs are done when the opportunity arises. The decision to maintain a component is based on opportunities that may or may not be triggered by the condition of a component. [54]

An example of this maintenance strategy can be found in offshore windmill industries, were once in 12 to 18 months a service visit to the offshore wind turbine is demanded. [78]

3. Corrective maintenance

Corrective maintenance is a reactive form of maintenance and is emergency based. Only repairs are done when a component malfunctions or fails. This may cause a general shutdown of the complete system, which can lead to high production stop cost. The motto of this type of maintenance is ‘If it isn’t broke, don’t fix it’.

Activity to repair the component was not scheduled beforehand. No money is spent on maintenance until a machine or component fails to operate. The drawback of this type of maintenance are high spare parts inventory cost, high machine downtime, high overtime labor costs and low production availability. [76]

Corrective maintenance is very often applied next to a preventive maintenance strategy. In industries where conveyor belt systems are used, this very often means replacement of broken idlers which have failed during the scheduled maintenance activities.
4. Predictive maintenance

Mobley states that ‘predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation.’ A predictive maintenance management program is used with monitoring equipment, for example vibration monitoring systems or thermography measurements. These monitoring systems obtain the actual operating condition of the system. Based on the acquired data, schedules of all maintenance activities on an as-needed basis are made. Predictive maintenance includes a comprehensive maintenance management program that optimizes the availability of machinery and reduces the cost of maintenance. It also aims to improve the productivity, product quality and profitability of manufacturing and production plants. [76]

In wind turbine farms at land this maintenance strategy is applied by Oros. Before operation of the wind turbines the characteristics of the turbines were researched. Indicators related to a type of faults like fatigue on bearings or gears, lubrication wear, unbalance or misalignment are identified. During operation multiple accelerometers monitor the vibrations of the wind turbines in the farm and compare the measurements to history data.

Via a WiFi connection multiple wind turbines are connected to a system which can be accessed via the internet, as shown in Figure 87.

Based on the predefined indicators, failure or damage can be detected and a lifetime estimation can be made by a software system. With this data the moment for maintenance can be predicted with a decision-making system. [79]

![Network of a wind turbine farm for predictive maintenance](image)

According to ABB reactive maintenance in mining industries is 5 times more expensive than preventive maintenance and even 10 times more costly than predictive maintenance. [80] All four categories of maintenance can be applied to a conveyor belt system, but due to the cost savings predictive maintenance seems to be the most promising strategy for maintenance. If the moment maintenance is
needed can be predicted, the cost can be reduced because no unnecessary maintenance has to be done anymore.

### 3.3.4.3. Intelligent maintenance

The Transport Engineering and Logistics department of the TU Delft introduced a new form of maintenance for conveyor belt systems, intelligent maintenance. To set up intelligent monitoring and to automate the maintenance system, predictive maintenance is the strategy to take. Intelligence in this case is defined as the ability to make decisions based on information gathered through monitoring equipment or provided by the control system of the conveyor belt system. [54]

Five main steps towards automated maintenance are:

1. Visual observation and inspection of critical conveyor belt system components followed by human decision-making and manual maintenance and control activities.
2. Automated monitoring (with sensors) of critical conveyor belt system components followed by human decision-making and manual maintenance and control activities.
3. Automated monitoring (with sensors) of most conveyor belt system components followed by human decision-making and manual maintenance and control activities.
4. Automated monitoring (with sensors) of most conveyor belt system components followed by automated decision-making (computer) and manual maintenance and control activities.
5. Automated monitoring (with sensors) of most conveyor belt system components followed by automated decision-making (computer) and automated maintenance and control activities (robots).

[37]

A structure to intelligent maintenance of the idler rollers in a conveyor belt system was researched and is given in Figure 88.

![Figure 88 Structure of an intelligent maintenance system for idlers](image)

The first level in the system is the component level and is divided in three categories: infrastructure, software and accessories. Infrastructure concerns all kinds of civil constructions and or hardware, software and accessories the computer programs and subsystems involved.

The second level is the subsystem level, for intelligent maintenance there are four subsystems: data acquisition, decision-making, replacement and logistic control. [39]
In Figure 89 predictive and reactive maintenance is compared to intelligent maintenance. With intelligent maintenance an optimum can be found in reduced number of failures and costs.

![Figure 89 Cost compared to maintenance strategies](image)

**3.4. Section summary**

To control a conveyor belt system, different systems are available. Conveyor belt systems can be manually controlled, or operators can be supported with computer technology. Still a lot of unplanned maintenance activities happen and no data about the reliability of the system is available. To reduce the unplanned maintenance activities and to predict the moment of maintenance, methods can help to go to reliability-based control of a conveyor belt system.

Reliability of a system can be defined with different measures, for example the failure rate of components, time to failure, mean time to repair, availability and maintainability of the system or a reliability number which is an index for the wear of the system.

The relationship of reliability between components in a system can be parallel, in series or a combination of parallel and series. Three main failure categories can be categorized: failures due to operating load, failures due to environment and failure due to poor manufacturing quality.

To go to a reliability-based control for a conveyor belt system first the fault and failures of the system have to be diagnosed. In a conveyor belt system failure of the drive unit, pulleys, idlers and belt can occur. A failure mode and effect analysis (FMEA) is a method to find the probability of failure, the failure modes, consequence of failure and the probability of detection of failure in the system.

To know the condition of the conveyor belt system different techniques can be applied to monitor the condition of the system. The belt can be monitored based on belt cover, belt carcass, belt splice, belt thickness, belt speed, belt slippage, belt take up displacement and belt misalignment. The drive unit, pulleys and idlers can be monitored based on vibrations, power and torque, rotational resistance and temperature.
Failures and faults in the conveyor belt system must be prognosed as well. Reliability block diagrams, fault and event tree analysis, progressive reliability method, Bayesian networks, Markov models, Monte Carlo simulation, finite element method, discrete element method and destructive testing are all methods to help to prognose faults and failures in a system.

The capital expenditure for a conveyor belt system contains six categories: the idlers, the conveyor belt, the drive unit, the pulleys, the support structure of the conveyor belt system and the electrical equipment. The belt, idlers and the electrical equipment are the most expensive components of a conveyor belt system.

The exact maintenance cost of a conveyor belt system is unique for each application and depends on different factors. The cost is for example depending on the cost of personnel and equipment required to maintain the system, the cost of spare parts, the number of components of the system, the type and abrasiveness of material the system needs to convey, the daily operating hours and the reliability of the different components.

Different maintenance strategies can be applied: preventive, random, corrective and predictive maintenance. For reliability control of a conveyor belt system predictive maintenance is the most desired strategy, due to the cost savings. Predictive maintenance can be up to 10 times cheaper than a corrective maintenance strategy. Intelligent maintenance was introduced by TU Delft as a form of predictive maintenance supported by a decision-making system and monitoring equipment for conveyor belt systems.
4. Application of reliability control for conveyor belt systems

To some extent reliability control is applied to conveyor belt systems, this section will discuss the current state and some remaining issues.

4.1. Current state

Three main points characterize the current state of reliability control for conveyor belt systems:

1. At this moment only subsystems of conveyor belt systems are controlled with reliability-based control to some extent. For example only the belt is monitored, assessed, maintained and controlled based on predefined operational requirements (as mentioned in section 3.1.2), but not the drive unit and idlers in the conveyor belt system.

2. Very often signals of premature failure go unnoticed due to the lack of indicator data about signs of a components about to fail. This results in conveyor belt systems stopping at unplanned moments. Repair activities are still very often applied in a preventive or corrective way.

3. Some new technologies have been developed to monitor for example the condition of the idlers with RFID technology (see section 3.3.1.5), but are not sold in operational conveyor belt systems yet. A technique to monitor the condition of the idlers based on rotational resistance is only tested in a laboratory environment and is not yet suitable for large scale applications. These are only monitoring techniques without a control system, which means a human operator has to assess the data acquired from this monitoring equipment.

There are some examples of applications in conveyor belt systems that monitor and assess the condition of subsystems, most of them only assess the belt. These control systems can control the conveyor belt system by alerting an operator or by automatically stop the conveyor belt system when a critical failure occurs.

4.1.1. Application examples

Most of the acquired data from the conveyor belt system is send to a computer, which uses software to graphically show the data. Some examples of these complete monitoring and assessing systems (software and hardware) especially designed for the operation and control of conveyor belt systems are produced by:

- The Beltscan Pty Ltd (Australia) – Belt Guard system
  This system has several variants including the one with belt core scanning, measurement of covers thickness and longitudinal cuts preventing system with magnetic encoders as shown in Figure 90.
  It is offering a high-resolution system with up to 200 channels for 2500 mm wide belt applications.

[70]
In this system the number of damaged cords at any belt cross section is monitored 24/7 and the acquired data is referenced to a user-defined threshold. If this threshold is violated the main electrical enclosure receives a command and a halt relay is energized. The halt relay may be used to stop the conveyor belt system or to alert operational personnel. [82]

Figure 90 Schematic working principle of Belt Guard system [82]

- CBM Conveyor Belt Monitoring (Australia) – CBGUARD
  Apart from damage detection this system forecasts the operation life based on the velocity of covers abrasion. The software is able to generate holistic analysis of any kind of threat to the belt. Irregularities like holes, gauges, bubbles, foreign objects, protruding cords, edge damage, abnormal cover wear and insufficient belt cleaning can be detected and processed. Arising non-visual damages like broken or corroded cords can alarm the operator to take measures. The system of CBM is also capable of measuring the belt thickness and yields timely information about the upcoming need for belt replacement. [83]

Figure 91 The ‘Life Extender’ of CBM scanning the returning belt [84]

- Intron (Russia) – Introcon system
  This system is able to monitor up to 4 m wide belts, moving with speeds of up to 7 m/s. The scanner is placed on the returning belt, as shown in Figure 92. An eddy current is applied to the belt. It is lighter than the equipment used in magnetic field analysis. The device is able to detect individual broken missing cords, splice integrity of steel cord conveyor belts and measures the gap between broken cords in the splices. The data from the measurement equipment is downloaded in software, which graphically shows the defects on a computer. Assessment of data is not real time, this means
the system cannot be directly stopped if a critical failure is detected. The data acquired is used to see the condition of the system and can be used by operators to plan maintenance [85].

The systems are compared in Table 8.

<table>
<thead>
<tr>
<th>System</th>
<th>Monitored parameter(s)</th>
<th>Sensor technology</th>
<th>Condition assessment</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt Guard</td>
<td>Belt cover</td>
<td>Ultrasonic</td>
<td>Real-time</td>
<td>Can stop the conveyor belt if a critical failure is detected.</td>
</tr>
<tr>
<td></td>
<td>Belt thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Belt carcass</td>
<td>Conduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBGUARD</td>
<td>Belt cover</td>
<td>X-ray</td>
<td>Real-time</td>
<td>Automatically graphically marks damages and notifies about the severity of damage with software.</td>
</tr>
<tr>
<td></td>
<td>Belt carcass</td>
<td></td>
<td></td>
<td>Can give an estimation of lifetime expectation based on belt condition.</td>
</tr>
<tr>
<td></td>
<td>Belt thickness</td>
<td></td>
<td></td>
<td>Can stop the system in case of critical failure.</td>
</tr>
<tr>
<td>Introcon</td>
<td>Belt carcass</td>
<td>Conduction</td>
<td>After measurements</td>
<td>Maintenance strategy has to be determined by operator based on assessment of software.</td>
</tr>
</tbody>
</table>

*Table 8 Different systems for monitoring and assessment*

The CBGUARD system comes close to a reliability-based control system. It compares history data to the current data acquired from the measurements on the conveyor belt. Based on user defined target values gives a (rough) estimation of lifetime expectation of the belt. The system can also stop the conveyor belt system when a critical failure occurs. The operator can determine when maintenance activities are needed based on the expected lifetime.
4.2. **Remaining challenges**

There are still some issues remaining to be challenged to be able to apply reliability control to a conveyor belt system. These issues will be discussed briefly in the next paragraphs.

4.2.1. **Data interpretation**

Reliability control is based on data acquired from sensors placed on a conveyor belt system. This may lead to a huge amount of data. To correctly interpret this amount of data and to identify existing failures or the start of a failure can be difficult. It is important to know which data can be used to predict failure of a specific component and what data value is corresponding to a critical failure.

4.2.2. **Failure prediction uncertainties**

It will always remain impossible to predict the moment a component of a conveyor belt system is going to fail with 100% certainty. Although there are different methods to estimate the moment of failure, due to imperfections or manufacturing errors it still might happen that a component fails at an unpredicted moment.

4.2.3. **Measurement uncertainties**

There might be uncertainties in the measurements within a conveyor belt system resulting from the applied monitoring techniques. For example, external factors like temperature rise in the environment of the conveyor belt system may lead to an increased temperature measurement of the equipment. Other environmental issues like high humidity, ventilation or dust might result in disruptions of the measurements.

The accuracy of the monitoring equipment might not be sufficient to notice small changes in the conveyor belt system, which might result in unnoticed failures in the system.

It is also possible that the system behaves differently during start-up or cool-down procedures. This might result in extra or more intense vibrations of the system. The control system might ‘think’ that the system is about to fail, which isn’t the case.

A sensor also has the possibility to wear and fail, which means the monitoring equipment isn’t responding correctly or no measurement data is received anymore from that specific sensor. This might lead to the monitoring of a failure that might not even exist. So, the reliability of the monitoring equipment has direct influence on the reliability of the conveyor belt system.

If all measurement equipment is connected via a wired network, electromagnetic interference, radio frequency interference or electrostatic interference (noise or also called signal interference) might occur. Proper shielding of the cables should be applied to prevent this type of error.
4.2.4. **Unsuitable lay-out for automated maintenance equipment**

There is some equipment available to replace the idlers of a conveyor belt system with robot technology, as will be discussed in section 5.2.7. To be able to apply this type of automated maintenance equipment the conveyor belt system must be suitable to fit a robot or to place a vehicle with maintenance equipment next to the conveyor belt. In for example a conveyor belt in a narrow mine shaft, there is no space to move a large vehicle next to the belt system.

4.2.5. **Monitoring system complexity**

The initial investment cost of the monitoring system can exceed the cost savings. By increasing the complexity of the monitoring system, for instance by adding more sensors or by applying more accurate monitoring equipment, a significant saving can be gained in the operation of a conveyor belt system. Although the savings might increase, the capital expenditure may increase even more than the savings. Cost savings are limited by the capability of the monitoring system and the operating condition of conveyor belt system. Excessively increasing the complexity of the monitoring system will result in a loss rather than a gain on the net savings. The net saving should be maximized by means of system integration with the minimum number of employed monitoring equipment. Figure 93 shows the return on investment related to the complexity of the monitoring system of a conveyor belt system. [37]

![Figure 93 Return on investment for monitoring equipment on a conveyor belt system](image)

**Figure 93 Return on investment for monitoring equipment on a conveyor belt system [37]**

4.3. **Section summary**

At this moment very often only subsystems of conveyor belt systems are reliability-based controlled. Signals of premature failures go unnoticed due to the lack of indicator data about signs of components about to fail. New techniques for reliability control are developed, but most of them are still applied in laboratory environment and not in practice.

The systems of Belt Guard, CBGUARD and Introcon have been discussed and have been compared. The CBGUARD system seems to be the most reliability-based control system for a conveyor belt system.

To facilitate a reliability-based control system, there are a couple of remaining challenges to overcome. The data interpretation of the monitoring equipment has to be optimized. Uncertainties in failure
prediction and measurements will always remain. The lay-out of (existing) conveyor belt systems will not always be optimal to facilitate the monitoring and or maintenance equipment. The increased complexity and the cost of the monitoring equipment will not directly lead to increased profits.
5. Opportunities

Applying reliability control to a conveyor belt system can have multiple benefits. New methods and techniques are developed suitable for the control of a conveyor belt system. However, there is still a gap between the current control systems and fully reliability-based control systems for a conveyor belt system.

5.1. Benefits

Applying reliability control on a conveyor belt system will result in reduced maintenance costs but the capital expenditure will increase. There needs to be a trade-off between the investment made and the gains resulting from maintenance activities that are only applied when needed. Only maintenance activities are applied at moments when there is a planned stop of the conveyor belt system. Due to the design based on predefined lifetime requirements, the components will wear under stated conditions. This means the power consumption of the system will not radically increase during operation and the chosen belt of the system will be optimal for the chosen application. The operational costs depend the most on power consumption and belt replacement (see section 3.3.4.1), so the operational costs and the downtime of the system will go down as well. The productivity is increased, because the unplanned stops are banned as much as possible.

The reliability of the system will increase as well, because the system will be designed to the predefined operational and lifetime requirements. The condition of the system will be monitored real-time and the remaining lifetime can be constantly assessed.

5.2. New developments for reliability control of conveyor belt systems

At this moment new techniques and methods are explored to be applied in the reliability-based control of conveyor belt systems.

Especially the intelligent maintenance techniques mentioned in section 3.3.4.3 can be supported with some of these new techniques. Intelligent maintenance relies on data acquired from the measurement systems present in a given conveyor belt system.

5.2.1. Big data

The type of data or information that must be stored for a reliability-controlled system may lead to Big Data. Big Data is described as a voluminous amount of structured, semi-structured and unstructured data that has the potential to be mined for information. Big Data is often categorized in three categories: a wide variety of data, extreme volume of data and the velocity at which the data must be processed.

[86]
In the smart idler concept introduced by Pang and Lodewijks [52] shows that if for example every five minutes each individual idler is asked to provide its temperature and battery status, it will lead to a large database that may need to be stored in the cloud. The advantage of having this Big Data in this concept is that it will be possible to detect deterioration of the idlers over time. Big Data can provide insight in the time available between an idler’s temperature passing the threshold value and the idler stopping to rotate. It is also possible to form a smaller database if only the ID’s of those idlers are stored of which the temperature passed the threshold value. The latter data can also be deleted as soon as an idler has been replaced. The prime goal of these analytics of the data is to the question at what rate the idlers deteriorate. This data is essential for the planning of (preventive) maintenance activities.

The effectiveness of a system to assess the condition of a conveyor belt system primarily depends on the use of a decision supporting system. When adequate inference rules are applied, the system can increase the effectiveness and shorten the time to take a decision. [87]

5.2.2. Internet of Things (IoT)

A new opportunity for a knowledge-based system for a conveyor belt system was introduced by Lodewijks [88] and is the Internet of Things. IoT has multiple definitions, by Miorandi [89] IoT is defined as ‘interconnecting physical objects with computing and communication capabilities across a wide range of services and technologies’, with physical attributes at the base of the definition. Gubbi [90] emphasis the use of platforms and the cloud, according to him IoT is perceived as ‘interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework (…) with Cloud computing as the unifying framework’. Atzori [91] defines IoT from a network perspective as ‘things or objects, which through addressing schemes interact with each other and cooperate with their neighbors to reach common goals’.

The concept introduced by Lodewijks was to connect the idlers of a conveyor belt system to the internet and make the information available 24/7 at any location. A communication network has to be set up to send the information of each individual idler (node) to the internet. The nodes in the network have to be able to send and receive data. RFID technology is a technology that can be applied for this network. This technology has a limited range [92], so it can’t be applied for long ranges, but it can send the information from one idler to the neighboring idler and form a data transmission network. A possible network to transfer the data to a devise that is coupled to the internet is in Figure 94. The network is built up every time an idler starts to transmit data, the path used for data transmission is not fixed. [88]
For the idlers in the network coupled to the internet, three different operational modes can be distinguished:

- **Internal activation mode**
  When the temperature of the idler exceeds the threshold value, the node is activated and starts to transmit its identity. If required, it can also transmit its temperature and status of the battery. This option will be used initially to determine the correct threshold value for the bearing and roll temperature. The threshold is influenced by ambient conditions and the type of application.

- **Central external activation mode**
  It is assumed that if an idler does not transmit its identity, the idler temperature is below the threshold value. It is also possible that for some reason the node in the idler is malfunctioning or it does not have enough power to be able to transmit data. For this case the idler temperature might be above the threshold value without the node transmitting data. By periodically requesting each node to identify itself and report its temperature and battery status, it is possible to check whether the nodes are still correct functioning. If the node does not respond to the request it can be considered broken and needs to be replaced.

- **Local external activation mode**
  A node of an idler is activated to transmit the same data if a neighboring idler is transmitting data to that node. This mode is used to either support the central request for identification of specific idlers or for the transmission of the identity and temperature of an idler whose temperature has exceeded the threshold value. [88]

### 5.2.3. Inspection robot

For large conveyor belt systems, it is very expensive to monitor each individual idler in the system. It might be possible to apply mobile sensors, which are placed on a robot that moves along or over the conveyor belt system. The robot transfers its data via a wireless network to a central control system.
An example of this way of inspection was introduced by Yang [93], with a concept for an infrared thermography inspection robot, as shown in Figure 95. An infrared sensor is placed on a cart which moves over a rail of the conveyor belt. This robot makes infrared thermal images of the components of a conveyor belt system which can be assessed by an external computer system.

![Figure 95 An infrared thermography inspection robot](image)

Not only robots can be applied, but also drones can be used to inspect the conveyor belt systems over a long distance. Tests have been performed with a drone equipped with a high definition camera, a microphone for audio recordings and a thermographic camera for thermographic inspection. [22]

### 5.2.4. Fuzzy logic

Decisions regarding maintenance in a conveyor belt system can also be supported with fuzzy logic. It is a form a causal modeling which is based on Bayesian methodology. With Bayesian methodology can model uncertainties in a system. The fuzzy logic method can diagnose failure situations of the conveyor belt system and decides if maintenance activities must be performed with less or without human efforts. Fuzzy logic is used to update and define the prior and likelihood probabilities for Bayesian interference. It is capable to evaluate the system situation and to denote the most possible failure causes to the user, as seen in Figure 96. [87]

![Figure 96 Fuzzy logic applied in the decision making system](image)

Applying fuzzy logic decision-making in a conveyor belt system provides:

- Objectification of the monitoring results.
- Consistent results between different monitoring equipment.
• A straight forward advice for maintenance.
• Fuzzy interpretation of the observations.
• Combination with other information sources. [94]

5.2.5. Knowledge-based expert system

A different approach to support the maintenance system is a knowledge-based expert system. In this system existing knowledge is implemented, for example to assess the decrease of the condition of the idlers. When a system is new, mostly not much information is known about the parts, so an expert has to invest a considerable amount of time into identifying monitored situations. The expert must decide whether the situation is faulty or not and how the system can be restored to an acceptable state. An example of an expert based control system for a conveyor belt system is given in Figure 97. [21]

![Figure 97 A multi-agent structure for control of a conveyor belt system [21]](image)

5.2.6. Computer-aided maintenance management system (CMMS)

A decision-making subsystem has to decide based on the acquired data if maintenance is needed. The decision-making process for maintenance activities can be aided with computer tools. An example of such a tool is computer-aided maintenance management system. The main functions of this type of software are processing and recording the acquired data, controlling the measuring equipment and communicate with the user.

In the concept of CMMS, the monitoring device can be transformed into an intelligent system that can independently respond to the changing operating conditions. It can eliminate conditions that cause for example belt breaks, by anticipating on the consequences of their occurrence.

This way the system can continuously monitor (supervision and safeguarding) the state of the analyzed object. Depending on the application, it can be used to support decision-making to ensure proper operation of the object, see Figure 98, or to prevent failure by control of the object, as shown in Figure 99. [95]
5.2.7. Automated replacement equipment

By controlling the object itself an automated maintenance system can be applied. This control system can be supported with robotized maintenance equipment.

5.2.7.1. Robotic Idler Replacement system

An example of a robot that is capable to automatically replace the idlers in a conveyor belt system is the Robotic Idler Replacement system of SCOTT Technology, originally developed by Machinery, Automation and Robotics (MAR). This technology is referred to as Robotic Idler Change-out (RIC). A robot is placed on a utility vehicle that drives next to the conveyor belt, as shown in Figure 100. A human-machine interface is used to control the RIC.

The manipulator is presented to the conveyor belt assembly, the RIC scans the conveyor idler frame and belt. The scanned information is used to position a lift unit under the belt, clamp to the frame and lift the belt. By lifting the conveyor belt, the damage idler can be removed and replaced, stowing the failed idlers on the vehicle. [96]

An advantage of this system is that maintenance can be applied to the conveyor belt system, without having to stop operation. It also gets people away from doing the difficult task of idler replacement. [97]
5.2.7.2. Spidler

A system that has an automated monitoring and replacement system is the Spidler of Sandpit Innovation Pty Ltd. and is shown in Figure 101. The Spidler moves over the conveyor belt on a rail with a speed up to 6 km/h. Laser scanners scan the idler and the frame prior to replacement of the idler. Two pairs of interlocking lifting arms allow the belt to be lifted. A rotary table-mounted robot is used to gain access to the side of the belt. An idler gripper assembly replaces the idlers via the side of the conveyor belt. The gripper is equipped with scanners for position monitoring and thermographic cameras for condition monitoring. New and damaged idlers can be stored on the carriage of Spidler. [98]
5.2.8. **Implement new maintenance strategy**

According to Lodewijks intelligent maintenance can be implemented in four different ways: [54]

1. Only forward inspection, assessment of data immediately after inspection, servicing if required. No maintenance activities on return. It is assumed that the maintenance trolley has sufficient data processing equipment on board to perform the data mining function.
2. Both forward and on return servicing and inspection. Assessment of data right after inspection. It is again assumed that the maintenance trolley has sufficient data processing equipment on board to perform the data mining function.
3. Only forward inspection, maintenance activities only on return. Data mining after inspection, but before return. Data mining is still performed on board of the maintenance trolley, either during inspection or upon arrival at the tail of the system.
4. Only forward inspection, assessment of data upon arrival at the tail, maintenance activities on return. The acquired data has to be transmitted to a central computer system that, after processing the data, dispatches a servicing list to the trolley or robot.

Big data, Internet of Things and the inspection robot or inspection drone seem to be promising for the fault and failure diagnoses of the conveyor belt system. Fuzzy logic and knowledge-based expert system can be applied in the fault and failure prognosis. The computer-aided maintenance management system, automated replacement equipment and the new maintenance strategies can be applied in the maintenance strategy applied to reliability-based control of a conveyor belt system.

5.3. **Discussion**

To fill the gap between current and future state, data about the reliability of components should be fully integrated in the control system. The control system should compare data about signs of failure of components (determined before operation) to real-time data acquired from the monitoring system. This way the system knows when failure of a component is about to happen.

The planned stops of the conveyor belt system are optimal moments for maintenance, because no operational time is wasted. If the moment of failure of a component can be predicted, the best moment for a planned stop of the conveyor belt system can be chosen by an integrated decision-making system.

The current systems are often expensive and the data acquired from these systems are hard to interpret for the maintenance staff. So the control system should report results in such a way that the user can easily understand what the system is monitoring. The mobility, ease of assembly and the ease of operation should be optimized for the user.

If the control system remarks signs of a failure in an earlier stage than predicted, the control system could for example turn down the speed of the conveyor belt system to reduce the speed of wear. In
this way the system is still able to remain in operation until the next planned stop of the conveyor belt system, without having to stop for a critical failure at an unplanned moment.

The maintenance staff can be notified by the system in advance, to let them know what components need to be replaced at the next conveyor belt stop. Components needed for repair might even be ordered automatically by the control system, so no replacement parts need to be stored in large numbers anymore. If the conveyor belt system is equipped with automated maintenance equipment, the control system can be deployed automatically.

5.4. Section summary

A reliability control system for a conveyor belt system comes with different opportunities, for example reduced maintenance costs, less downtime of the system, lowered operational costs and increased productivity and reliability.

New developments like big data and internet of things can help with the interpretation of the acquired data from the monitoring equipment. An inspection robot can be applied to aid with monitoring of large conveyor belt systems. Fuzzy logic, knowledge-based expert systems and computer-aided maintenance systems can help with making decisions for maintenance. Maintenance itself can be automated with a robotic idler replacement equipment. Four different ways to implement an intelligent maintenance strategy have been discussed as well.

To implement reliability control on a conveyor belt system, data about reliability of the different components of the system has to be implement in the control system. Maintenance activities should be planned on the most optimal moments based on the condition of the components. Only planned stops should be applied.

The ease of use, mobility and ease of assembly of the monitoring and control system should be optimized. The maintenance staff should be able to easily understand what is going on in the conveyor belt system.

The control system can help to advise which maintenance activities are needed for the conveyor belt system. Fully automated maintenance equipment can even be deployed automatically by the control system when needed.
6. Conclusion

Efficient and effective diagnosis of a conveyor belt system is essential for continuous assessment of the system's condition, to prevent major failures and to prolong the conveyor belt system service life. Different monitoring techniques can perform real time or interval-based measurements of critical components to monitor the condition of the conveyor belt system.

Developing a reliability-controlled conveyor belt system is possible, by first defining the required function and required life time in the process of designing the system. Different methods can be used in the design phase of a conveyor belt system to comply the system design to the operational requirements. Critical failures that lead to a stop of the conveyor belt system, for example belt tear, belt run-off or a broken drive unit, must be determined with for example a failure mode and effect analysis. Monitoring techniques can be applied to monitor the critical components, very often the belt and drive unit, during the operation of the conveyor belt system. Assessment methods help to assess the condition of the components real-time and decision-making strategies assist to determine the moment of maintenance. Optimally all maintenance activities take place at moment the conveyor belt system has a planned shutdown.

In a reliability-based control system, signs of increased wear occurring in an earlier stage than predicted can occur, the control system could for example turn down the speed of the conveyor belt system to reduce the speed of wear. In this way the system is still able to remain in operation until the next planned stop of the conveyor belt system, without having to stop for a critical failure at an unplanned moment.

The control system can also be integrated in the inventory of spare parts for the conveyor belt system. If the control system knows what components need to be replaced at the next planned maintenance stop, the system might be able to automatically order the needed components. This way no extra unneeded components are stored or bought.

If the conveyor belt system is equipped with automated replacement equipment it is possible to automatically deploy the equipment by the control system at the planned maintenance stops.

There are still some challenges to be dealt with before a complete reliability-controlled conveyor belt system will be fully operational. In example uncertainties in failure prediction, interpretation of huge amount of data acquired from the monitoring equipment, uncertainties in sensor measurements and reliability of the monitoring equipment.
An optimum should be found in the cost of a reliability control system in regard to the return on investment and the extra gains when applying a reliability control system on a conveyor belt system. Applying one or more or more advanced sensor technologies will not always be the best solution in regard to the added costs.

New developments like automated idler replacement robots, smart idlers with RFID technology, intelligent maintenance, computer-aided maintenance management system, decision-making strategies based on fuzzy logic, knowledge-based expert system, Big Data and Internet of Things can aid to form a reliability-based control for a conveyor belt system.
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## Appendix A - FMEA

### Tables for criteria analysis

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<thead>
<tr>
<th>Effect</th>
<th>Criteria: severity of effect</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazardous without warning</td>
<td>Very high severity ranking when a potential failure mode affects safe operation and/or involves noncompliance with regulations without warning.</td>
<td>10</td>
</tr>
<tr>
<td>Hazardous with warning</td>
<td>Very high severity ranking when a potential failure mode affects safe operation and/or involves noncompliance with regulations with warning.</td>
<td>9</td>
</tr>
<tr>
<td>Very high</td>
<td>Product/item inoperable, with loss of primary function.</td>
<td>8</td>
</tr>
<tr>
<td>High</td>
<td>Product/item operable, but at reduced level of performance. Customer unsatisfied.</td>
<td>7</td>
</tr>
<tr>
<td>Moderate</td>
<td>Product/item operable, but may cause rework/repair and/or damage to equipment.</td>
<td>6</td>
</tr>
<tr>
<td>Low</td>
<td>Product/item operable, but may cause slight inconvenience to related operations.</td>
<td>5</td>
</tr>
<tr>
<td>Very low</td>
<td>Product/item operable, but possesses some defects (aesthetic and otherwise) noticeable to most customers.</td>
<td>4</td>
</tr>
<tr>
<td>Minor</td>
<td>Product/item operable, but may possess some defects noticeable by discriminating customers.</td>
<td>3</td>
</tr>
<tr>
<td>Very minor</td>
<td>Product/item operable, but is in noncompliance with company policy.</td>
<td>2</td>
</tr>
<tr>
<td>None</td>
<td>No effect.</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 9 Severity evaluation criteria [35]*

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Possible failure rates</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high: failure is almost inevitable</td>
<td>≥ 1 in 2</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1 in 3</td>
<td>9</td>
</tr>
<tr>
<td>High: repeated failures</td>
<td>1 in 8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1 in 20</td>
<td>7</td>
</tr>
<tr>
<td>Moderate: occasional failures</td>
<td>1 in 80</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1 in 400</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1 in 2.000</td>
<td>4</td>
</tr>
<tr>
<td>Low: relatively few failures</td>
<td>1 in 15.000</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1 in 150.000</td>
<td>2</td>
</tr>
<tr>
<td>Remote: failure is unlikely</td>
<td>≤ 1 in 1.500.000</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 10 Occurrence evaluation criteria [35]*

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<table>
<thead>
<tr>
<th>Detection</th>
<th>Criteria: likelihood of detection by design control</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute uncertainty</td>
<td>Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control.</td>
<td>10</td>
</tr>
<tr>
<td>Very remote</td>
<td>Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>9</td>
</tr>
<tr>
<td>Remote</td>
<td>Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>8</td>
</tr>
<tr>
<td>Very low</td>
<td>Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>7</td>
</tr>
<tr>
<td>Low</td>
<td>Low chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>6</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>5</td>
</tr>
<tr>
<td>Moderately high</td>
<td>Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>4</td>
</tr>
<tr>
<td>High</td>
<td>High chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>3</td>
</tr>
<tr>
<td>Very high</td>
<td>Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode.</td>
<td>2</td>
</tr>
<tr>
<td>Almost certain</td>
<td>Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode.</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 11 Detection of failure evaluation criteria [35]
<table>
<thead>
<tr>
<th>Results</th>
<th>Exploratory</th>
<th>Detection</th>
<th>Occurrence</th>
<th>Severity</th>
<th>Recommended action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (RPN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk Priority</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 12 Example of a FMEA sheet [35]**