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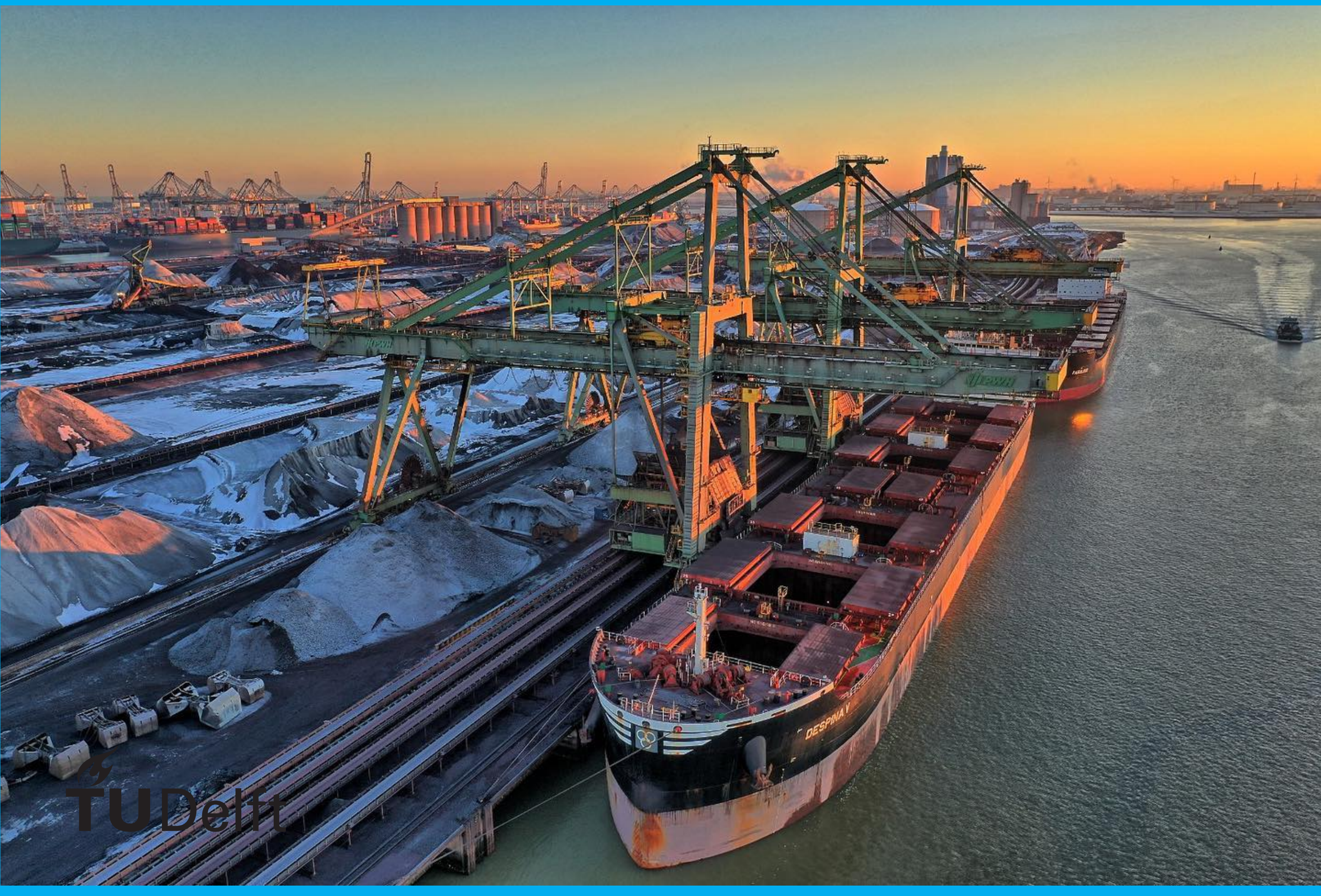

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A maintenance strategy for conveyor belt systems in a dry bulk terminal

by

K. S. de Vos

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Personal foreword

I started this thesis when I just carried my grandfather to his grave after collapsing at Christmas dinner '21. Trying to live up to his greatness in many different technical industries, I believe he is the true inspiration for both my father's as my own interests in mechanical engineering. I paused this thesis when my mother got sick in October '22 and I had to unexpectedly carry her within three months to her grave as well. Carrying their coffins was as hard as taking care of my father and brother after the unexpected loss of my mother. After a long break, my mental state got better and I could carry on with this thesis. In the last weeks my furry fiend Chester passed away as well. My sincere apologies that it took me so long for this to finish and my greatest thanks for the possibility to finish this thesis.

In honor of my grandfather, mother, and Chester.

Preface

This thesis will give insight in the creation of a maintenance strategy for a dry bulk terminal to reduce downtime and maintenance cost and improve operation and reliability. The thesis is performed at the dry bulk terminal of EMO B.V. and will use the existing data of the equipment that is installed on this terminal. Malfunctions happening during this thesis will be investigated as well.

EMO's dry bulk terminal handles mainly coal and iron ore. While the production of energy is shifting (from using coal) towards more sustainable solutions, coal and iron ore are still needed for the world as it is today. These raw materials are required for the steel industry, the creation of solar panels, bridges and cars.

This thesis will focus on different maintenance strategies of the equipment that are used to handle the dry bulk material. Reducing downtime and maintenance cost will make the equipment more efficient and leads to improved operation and reliability. In order to create a new maintenance strategy, the current strategies must be investigated as well as the malfunctions occurring on the terminal. For the literature studies several strategies of other terminals will be investigated too, as well as journals, patents and international standards.

K. S. de Vos
Delft, January 2022

Abstract

At a dry bulk terminal, coal and iron ore are transported in the open air by conveyor belts and handled by large (mainly automated) equipment. The dry bulk material is rough and the equipment is installed in the harsh environment of the harbour. With vessels continuously being unloaded by quay cranes and outgoing vessels and trains being loaded, the conveyor belts make lots of operational hours. With more than 27 kilometers of conveyor belts running at 4.5 m/s it is important these systems are maintained well.

To reduce downtime and maintenance cost, a new maintenance strategy will be created. Therefore, different maintenance strategies and methodologies will be explained and the current situation will be investigated. A new maintenance strategy will be created by using the FMECA method (Failure Modes, Effects and Criticality Analysis), where malfunctions of the conveyor belt systems will be prioritized according to their criticality. Malfunctions happening during the period of this thesis will be investigated and used as an example to proof the new maintenance strategy works. This strategy is applicable to other equipment and other terminals as well. In the end some future remarks will be discussed to further improve the new maintenance strategy.

Contents

Introduction

Dry bulk material, such as coal and iron ore, comes into the harbour by vessels in large amounts of loose cargo. Large quay cranes unload the vessels with grabbers and transport the dry bulk material via conveyor belts to the storage area, where the dry bulk material is stored by stacker-reclaimers in stacks in the open air. The dry bulk material can be reclaimed by the same equipment, transported via conveyor belts to outgoing vessels and trains, loaded by barge loaders and train loaders. At EMO B.V., 80% of the dry bulk commodities is transported to the German hinterland by train or vessel.

EMO B.V. is (one of) the largest dry bulk terminals of Europe, with an annual throughput of 60 million tonnes coal and iron ore. EMO B.V. has three 85 tonnes cranes and two 50 tonnes cranes for unloading the larger dry bulk vessels. EMO b.v. has three barge loaders for loading smaller vessels, one for seagoing vessels, and three train loaders (one especially for iron ore and two for coal) for loading trains which will transport the dry bulk material to the hinterland (mostly Germany). There are seven stacker reclaimers, which can both stack the incoming dry bulk material on storage piles and reclaim dry bulk material from the storage area onto conveyor belts for further handling and export. The storage area has a total capacity of 8 million tonnes and has specific areas for storing coal, iron ore, and sometimes more specialized dry bulk material, such as cokes or pellets. The terminal is equipped with over 27 kilometers of conveyor belts to transport the dry bulk material over the entire terminal. EMO B.V. also offers the service for washing and screening of the dry bulk material to separate the dry bulk material into different grades and qualities.

The dry bulk material is transported all over the terminal by conveyor belts. A conveyor belt system consists of an endless looped belt, which is made of rubber and often reinforced with steel wires or even with steel plates. The conveyor belt is driven by multiple electromotors, depending on the length of the conveyor belt. The belt is supported by different types of rollers - also called idlers - depending on their location and function. The belt is put under tension by a tensioning device or winch for optimal performance and starting solutions. The belt can travel horizontal or under an inclination (or declination) and most belts on the terminal can operate in both directions. Some conveyor belts are covered with corrugated sheets or completely covered in tunnels. The conveyor belt systems at EMO B.V. are regulated from the control room or operate automatically at a speed of 4.5 m/s.

To handle and transport all the dry bulk material 24/7, the equipment must be checked regularly for irregularities. The equipment at a dry bulk terminal is large, mostly operated automatically, and not without risk for human workers. It is important to stop malfunctions as soon as possible to prevent extreme failure consequences and possibly dangerous situations. Failure consequences include an increase in maintenance cost and unplanned downtime and a decrease in machine reliability, availability, and safety. Several condition monitoring solutions will be investigated in this thesis to limit failure consequences in dry bulk terminals. These solutions will be used for creating a new maintenance strategy with the goal to reduce downtime and maintenance cost, while increasing reliability of the equipment.

Aim and scope of this thesis

The goal of this thesis is to explore condition monitoring techniques and existing condition monitoring data to create a maintenance strategy to decrease failure consequences - such as unplanned downtime and maintenance cost - while improving reliability and safety of conveyor belt systems at a dry bulk terminal. Existing literature of condition monitoring techniques in dry bulk terminals will be investigated. Other condition monitoring techniques will be explored and investigated if applicable on conveyor belt systems in a dry bulk terminal. During this thesis some malfunctions (events) might occur, which will be investigated thoroughly to discover the initial causes and their consequences. These events will help in creating a maintenance strategy to prevent these malfunctions and their consequences in the future.

At the moment the dry bulk terminal of EMO b.v. contains a large amount of sensors with different purposes along the conveyor belt systems and a massive amount of data is collected. The aim is to analyze this data in such a way that the current state of the equipment can be determined. Eventually a strategy will be developed where the existing condition monitoring data is used and analyzed to not only be able to know the current state of the equipment, but also to be able to detect malfunctions in an early state and act upon it. By detecting malfunctions in an early state and acting upon it - either by notifying a human operator to look on site, pausing the operation or taking another action - it is possible to prevent failure consequences, such as unplanned downtime and higher maintenance costs.

Current situation and necessity of this thesis

Currently EMO b.v. follows two maintenance strategies. The first strategy is a run-to-failure maintenance strategy which is suitable for smaller components and for components that are installed in large quantities, like the idlers (over 100.000 installed). It is also used for equipment and components where condition monitoring would be rather expensive compared to a run-to-failure strategy. This strategy requires a large warehouse, a large investment in spare parts, and possibly maintenance for the spare parts if the parts get damaged in the meantime due to rust, for example.

The second strategy is a preventive maintenance strategy. Components will be replaced or maintained according to a schedule, which is either calendar based or based on the operation hours or the number of cycles, regardless of its condition. This means it is possible a component is replaced or repaired too soon, which leads to unnecessary downtime, waste, and (maintenance) costs. On the other hand, preventive maintenance might be too late for some parts. It is always possible that a part or equipment is functioning better or worse than the schedule indicates, even though the schedule is based on manufacturer's data and experience. This strategy is mainly used for components that are more expensive or contain lubricants (oil), like gearboxes and electromotors.

Besides these two types of maintenance strategies EMO B.V. has a lot of data from sensors installed on the equipment. Parameters like power, current, number of cycles, speed, are all collected at 10 Hz and saved to a large data warehouse for an average time of two weeks. The company is also exploring its possibilities in condition monitoring and is currently running several tests by different companies in several parts of the conveyor belt systems and other equipment. This data is analyzed by the testing companies, but EMO b.v. has insight in some of the data as well. The company is willing to investigate in more condition monitoring solutions to be able to surveil the equipment from distance when operating automatically.

The conveyor belts operate in the open air at a speed of 4.5 m/s with the consequence of wear and damage. This means there is a need for constant surveillance to be able to detect malfunctions in an early state to prevent major incidents from happening. But since the belts are automatically operated, there is no direct visible feedback from a human operator who might spot (early) damage in the belt. Because of the enormous total length of the conveyor belts (over 27 kilometres), it is almost impossible to manually inspect all the conveyor belts continuously without hiring an endless amount of human workers and turning off the belts. In practice every belt is inspected only once a month, or even less for the belts that are not operating that often. Damage in the belt is only noticed during a scheduled inspection (preventive maintenance strategy) or by coincidence (when someone passes by). This might be too late. Ideally a malfunction or damage is recognized in an early state, so it could prevent creating larger failure consequences, such as more damage or becoming a dangerous situation. When it comes down to detect failure in an early state, condition monitoring techniques could be a solution.

Besides decreasing unplanned downtime and maintenance costs, it is important to achieve the highest possible level of safety and reliability of the conveyor belt systems. Human operators will still be working on site and might have to interact with the equipment. With human safety being of utmost importance, a safe and reliable workplace must be provided. With condition monitoring the equipment at the terminal can be monitored closely and whenever a malfunction is detected, the human operators on site must be notified or the operation must be halted to prevent a possibly dangerous situation, depending on the state of the malfunction. This decision making is part of a predictive maintenance strategy, which will be the ultimate goal for this terminal, but out of the scope for this thesis.

Research questions

The main research question will be:

> *"How could existing condition monitoring data be used to create a new maintenance strategy for a dry bulk terminal?"*

The sub research questions will be:

- *"What is EMO B.V. and what equipment in installed? What area or piece of equipment is most promising to improve its maintenance strategy and why?"*
- *"What is condition monitoring and what are different maintenance strategies? What is EMO's current maintenance strategy?"*
- *"What condition monitoring data is available at EMO, how is it obtained, and how can this be used for planning maintenance?"*
- *"Which methodology is best to create a new maintenance strategy?"*
- *"How is this methodology implemented and how is the maintenance strategy kept up to date?"*

Conclusion

After exploring different maintenance strategies and methodologies to create a new strategy, the FMECA method (Failure Modes, Effects, and Criticality Analysis) was chosen to create a new maintenance strategy. This method makes use of the existing condition monitoring data and investigates the different malfunctions (failure modes), with their causes and consequences (effects). Based on a risk assessment a criticality analysis is done to prioritize the different failure modes. This method will create a new maintenance strategy for the conveyor belt systems, but is applicable to the other equipment and to other terminals as well. Following the ISO standard 60812, this method is accepted worldwide.

Regarding the state of the art, there is quite some research done on condition monitoring in dry bulk terminals, especially for conveyor belts. But not a lot of this research is performed in practice. EMO B.V. has a lot of condition monitoring data, but is not yet using it optimally for its maintenance strategies. The dry bulk terminal can benefit more from the existing data than is currently the case.

The FMECA method is used to create a new maintenance strategy. While this method is not unheard of, it is not yet commonly used in dry bulk terminals. With limited research performed on this methodology for dry bulk terminals, EMO B.V. could become one of the first dry bulk terminals adopting this method. While the FMECA method is performed for conveyor belt systems in this thesis, it is widely applicable and can be adjusted for the other equipment as well. The FMECA method can be implemented in other terminals as well.

Thesis outline

Every sub research question will be discussed in their own chapters. The first chapter will introduce the dry bulk terminal of EMO B.V. and explain why the conveyor belt systems are the main focus of this thesis. The second chapter will explain the different condition monitoring and maintenance techniques and also address the current situation at EMO B.V. This chapter also explains how the current situation can be improved. Chapter three will address the existing condition monitoring data at EMO B.V., how it is obtained and how this can be integrated in a new maintenance strategy. The following chapter will discuss different methodologies and the criteria to create a new maintenance strategy for this dry bulk terminal. Chapter 5 will explain how this strategy can be implemented for conveyor belt systems on a dry bulk terminal. Chapter 6 will show some examples from malfunctions that happened during the time this thesis was performed as three separate case studies. The conclusion will answer the main research question and future remarks and gaps will be discussed afterwards.

1

Introduction of EMO B.V.

This chapter introduces the dry bulk terminal of EMO B.V. and will answer the sub research question *"What is EMO B.V. and what equipment in installed? What area or piece of equipment is most promising to improve its maintenance strategy and why?"*. The first section will explain what a dry bulk terminal is and briefly discuss its components to answer the first part of this sub research question. The company where this thesis was performed (EMO B.V.) will be used as an example of a dry bulk terminal. The second section will discuss how a certain piece of equipment or area on the terminal is chosen as the focus of this thesis. The third section will explain why the conveyor belt system is chosen and explain the entire conveyor belt system and its components. This section answers the second part of the sub question. The last section will conclude this chapter.

1.1. The dry bulk terminal of EMO B.V.

EMO B.V. is operating at the Maasvlakte II since 1973 and has grown rapidly to one of the largest terminals in Europe which handles dry bulk material [14]. Dry bulk material refers to a solid material which is transported in large quantities as loose cargo, which means it is not stored in containers or other units. The dry bulk handled in this terminal mainly consists of coal and iron ore and is eventually used in the silicon industry, steel industry and the energy sector. Coal is used for power generation in the energy sector and as raw material for solar panels (for example) in the silicon industry. Iron ore is used for the steel industry in combination with coal to produce structures like cars, bridges and wind turbines.

The terminal unloads bulk material from vessels with the use of quay cranes and then stores the material in storage areas on the terminal or loads the material on to vessels, trains and barges. This is all done by different equipment that is operating on the terminal. Some of this equipment is (semi-)automated or has the possibility to be operated remotely from the control room. Other equipment is human operated on site. The different types of equipment operating on the terminal will briefly be discussed in the following subsection.

Besides loading, unloading, and storage of bulk material, EMO B.V. offers several additional (value adding) services to its worldwide customers, like washing, screening and blending of coal. On a daily basis EMO B.V. can wash and screen 2500 ton of coal. Washing coal will remove impurities in the product. Screening is done after washing and separates the coal into different sizes and different grades of quality. When required, EMO B.V. can blend the coal of various grades (size or quality) together to meet the customer's specifications. This is done in blending silos, of which EMO B.V. has a total capacity of 7000 ton.

With a guaranteed depth of 21.65 meters along the 1350 meters long Mississippi quay, EMO B.V. can moor the world's largest seagoing vessels (even New Panamax size vessels with a length of 366 meters). With the ability of loading and unloading the world's largest vessels, the harbour can act as a hub for the rest of Europe. This way, almost 80% of dry bulk commodities is transported to the German hinterland by train or vessel. Via the Betuwelijn the terminal of EMO B.V. is directly connected to the European rail network, which makes fast, clean and inexpensive access to the hinterland possible.

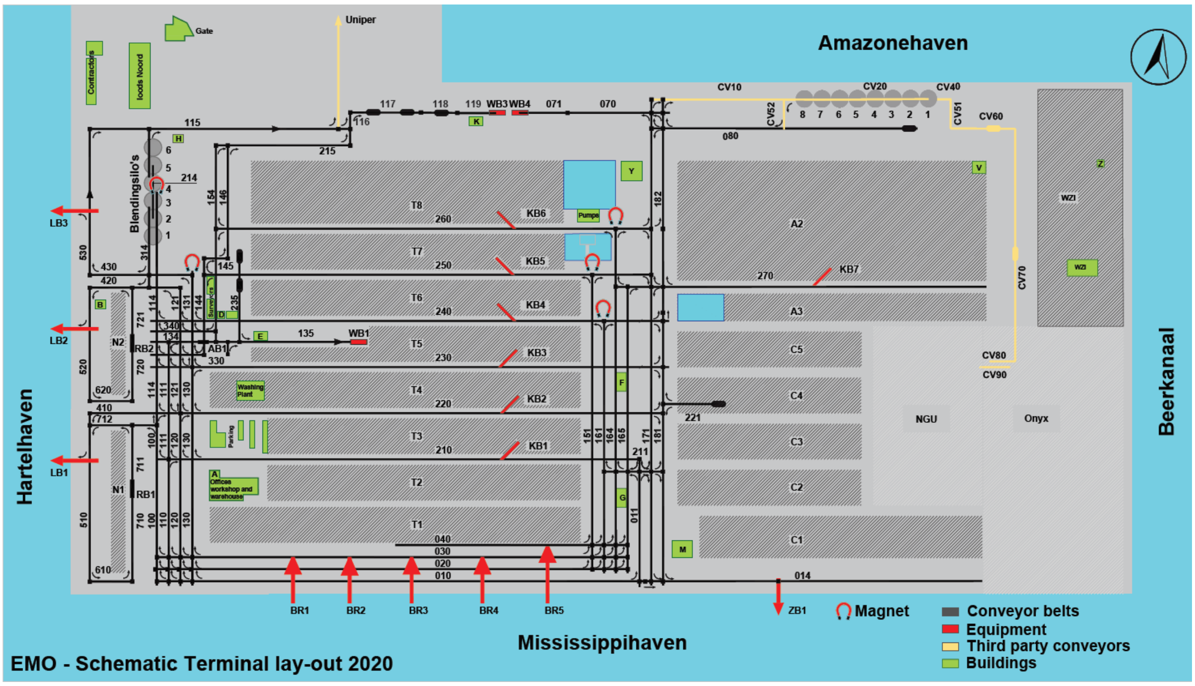


Figure 1.1: Schematic lay-out of the EMO terminal 2020 (Intranet)

For a visual understanding of the terminal, a schematic layout is shown. In figure 1.1 the black lines represent the conveyor belts on the terminal. On the West side there is the Hartel harbour where the three barge loaders load bulk material onto smaller vessels (indicated by red arrows). On the South side quay, the Mississippi harbour, larger vessels are unloaded and the dry bulk material will be sent to the storage areas via different conveyor belts and a stacker-reclaimer. The stacker-reclaimers are indicated with ”KB” and a number, showing a red diagonal line. The quay cranes are indicated by the red arrows pointing towards the terminal. The sea-going vessel loader is indicated with a red arrow pointing towards the water on the right side of the Mississippi harbour. The blue areas represent water, which also accounts for three water basins at the terminal. The green parts on the map represent buildings like offices, electric stations and more. The storage areas (regular storage areas as well as the emergency storage areas) are indicated by the darker gray rectangles on the map. Yellow lines are conveyor belts which are not under the management of EMO B.V. All these components will be explained in the following section.

Equipment on a dry bulk terminal

Once it is clear what a dry bulk terminal does in general - loading, storing and unloading coal and iron ore - the different equipment at the terminal can be clarified. Starting with unloading coal and iron ore from incoming vessels, the quay cranes will be the first to discuss.

Quay cranes

Along the 1350 meters long Southern deep sea quay of the Mississippi harbour, five cranes are located for unloading dry bulk material from the vessels, with an average unloading capacity of 100.000 ton per day. Two of these cranes can handle 50 ton at a time, where the other three newer cranes can handle 85 ton at a time. The first crane (bridge 1; BR1) is currently retired with over 40 years of service. It is only used for loading specialized bulk - like cokes, which are specialized packages of coal - onto vessels. This crane will eventually be renovated or replaced.

The cranes can travel alongside the quay, which makes the berthing location for vessels more flexible. The quay is long enough to unload five smaller vessels or three large vessels at the same time. Now that crane 1 is retired, a maximum of four vessels will be unloaded at the same time. It also happens that two cranes are simultaneously unloading the same ship, especially when it is a larger vessel with a large amount of dry bulk.

The cranes are fully automated, but can be manually operated by a human operator inside the cabin. With real-time data from sensors a visual image is created where the operator sees exactly where the grabber is with respect to the quay, the crane, the load and the vessel. Due to recent company/ board changes, the company prefers human operators to operate the cranes from the cabin on the crane.

Figure 1.2: Cranes 1, 2, and 3 at the terminal of EMO B.V. (picture taken at 11 January 2022);

The quay cranes are equipped with different sized grabbers created by the Dutch company NEMAG B.V. The grabbers have different sizes for the different dry bulk materials. Iron ore has a higher specific weight than coal, meaning that for the same weight, iron ore has a smaller volume. In order to not exceed the weight limit of the cranes, the grabbers for iron ore are smaller than the ones for coal.

After grabbing the dry bulk, the material will be thrown in a chute, of which the shutter is controlled remotely from the control room. After going through the chute, the dry bulk material falls on to the conveyor belts and will be transported over the terminal.

Figure 1.3: Iron ore grabbers, Kelly for scale (picture taken by photographer at 17 March 2022)

Barge loaders

Besides unloading vessels, there are also vessels coming to EMO B.V. collecting dry bulk material to transport it overseas. Three barge loaders, located at the Western quay of the terminal, are used for loading the dry bulk material onto the vessels. These barge loaders can also travel alongside the 900 meters long quay of the Hartel harbour and have a maximum loading capacity of 6000 ton per hour. The bulk material is transported directly from the conveyor belts of the barge loaders onto the vessels. The outgoing conveyor belt is perpendicular to the quay and it is possible to adjust height and length for optimal loading. See figure 1.4 for a photo of the barge loaders.

Figure 1.4: Left: Barge loader (EMO Intranet), Right: Sea boat loader ZB1 close-up (Intranet)

Sea-going vessel loader

The sea-going vessel loader is an automatic barge loader that loads dry bulk material onto the bigger sea-going vessels with a maximum capacity of 6000 ton per hour. The loading tip is more flexible than that of a regular barge loader as it is equipped with a tube that can extend and rotate (see figure 1.4). This makes it possible to load the dry bulk material under an angle, which results in more accurate and precise loading of vessels compared to the normal barge loaders.

Train loaders

Besides vessels, trains are also loaded with dry bulk material. The terminal of EMO B.V. is equipped with three automated train loaders with a capacity of 3800 ton per hour. One train loader is only used for loading iron ore, where the other two only load coal. These train loaders have the option to add Glycol, which acts as an anti-freeze. After loading a wagon, it will get topped off with paper pulp. This prevents the material from dust forming and possibly flying out of the wagons, since the trains are open on top.

When entering the train loader operating room, noticed is that there is no human operator around. In figure 1.5 the interior of the operating room is shown. A fully equipped control room is installed, even though the train loaders are fully automated. The screens are fully functioning and showing everything the operator is doing from the central control room, including live views from the cameras which are installed inside and around the train loaders. Whenever a human operator comes to check if everything works properly, they can check what the main operator is doing and what is happening in the train loaders.

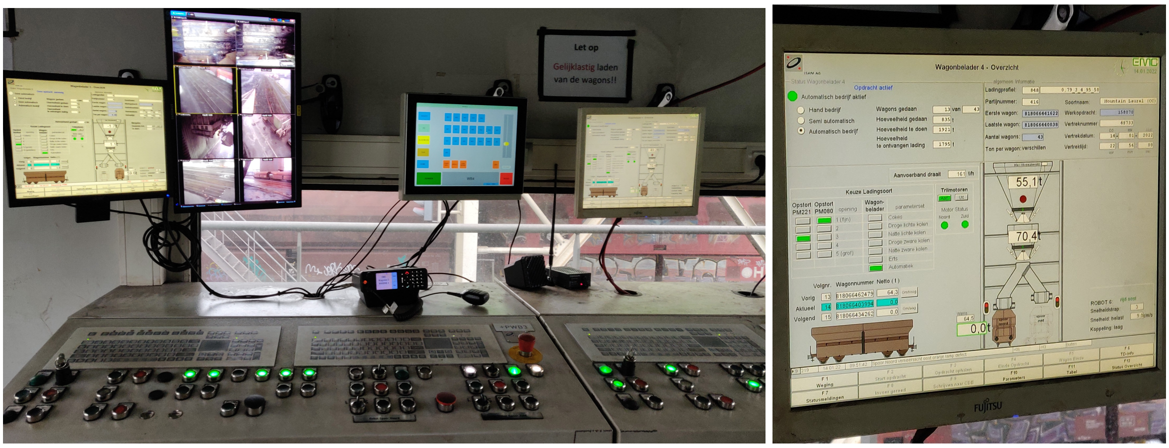


Figure 1.5: Left: Inside of the control room of the train loaders, Right: Close-up of operating screen (pictures taken at 14 January 2022)

Storage area

EMO B.V. has a storage capacity of almost eight million tonnes for coal and iron ore. The storage area is mapped and it is well known which areas of the storage area are reserved for different clients. It is possible that a client sends someone over to test the quality of their stored product, so it is important to map the storage area regularly.

Along belt 220 and stacker-reclaimer 2, there is more iron ore stored than coal. This is because this part of the storage area is located next to the train loader WB1 that only handles iron ore. The stacker-reclaimers stack the dry bulk material in piles and these are monitored regularly by EMO B.V. to prevent combustion, dust forming and collapsing of the piles due to liquefraction.

In figure 1.6 a photo is shown with different storage piles. The five quay cranes are shown in the background (crane 1 on the left, crane 5 on the right). As can be seen in the photo, the coal piles are black and the iron ore piles are orange/ brownish. All the piles are covered with a white layer, this is a thin layer of paper pulp, which prevents the bulk from dust forming and loss of material. Besides preventing the bulk from dust forming and loss of material, the terminal prevents the bulk from spontaneous combustion by compacting the material. Compacting is the process where the bulk material gets stacked layer by layer and each layer will be rolled to eliminate any space for oxygen.

Figure 1.6: Storage of coal and iron ore at the terminal of EMO B.V. (picture taken at 14 January 2022)

Stacker-reclaimers

The terminal of EMO B.V. is equipped with seven stacker-reclaimers. This is a combination of a stacking machine and a reclaiming machine, hence their Dutch name ”Kombi”, of combination. Other terminals might have separate machines for stacking and reclaiming dry bulk material, but EMO B.V. chose to be equipped with the combined stacker-reclaimers with a maximum stacking capacity of 6000 ton per hour and a maximum reclaiming capacity of 4500 ton per hour.

Each stacker-reclaimer has its own storage area along its own - almost three kilometers long - conveyor belt for loading and reclaiming dry bulk material. All stacker-reclaimers on the terminal are fully automated, but can also be manually operated on site (from inside the cabin). The stacker-reclaimers are therefore equipped with GPS antennas, a 3D-laser scanner and a collision avoidance protector. The stacker-reclaimers are able to travel in East-West direction via rail to cover the entire area. It is also able to turn and to extend its head, which consists of an outgoing conveyor belt and a wheel of grabbers (see figure 1.7). Stacking is done in specialized manners and the storage area is organized by type of material, order size, quality, and client. To prevent collapsing of the storage piles, reclaiming is carefully done layer by layer.

In the layout will be seen that there are six stacker-reclaimers at the main area A1, while the seventh is located at area A2. The seventh stacker-reclaimer was built later when the terminal was reaching higher demands.

Figure 1.7: Left: Stacker-reclaimer at the terminal of EMO B.V., Right: Close-up of the bucket wheel (pictures taken at 29 April 2022)

Conveyor belt systems

All equipment on the terminal is connected to each other by conveyor belts. More than 75 conveyor belts with a total length of over 27 kilometers transport the bulk material around the entire terminal with a constant speed of 4.5 m/s. The conveyor belts are made of rubber and they are reinforced with steel cords. The majority of the conveyor belts has a width of 1800 mm varying in lengths up to 3500 meters! The conveyor belts are driven by multiple electromotors, stationed in the beginning and ending of the belt. The belt is put under tension by the tension device or a pulley, which is mostly located at one of the ends, close by one of the drive units. The drive units and tension device are remotely controlled.

The belt is supported by an enormous amount of idlers, hung in a steel frame. Every meter there are three idlers placed underneath the carrying belt perpendicular to the travel direction; the middle idler is horizontal and the outer two idlers are diagonal for optimal support of the belt. The returning belt is supported by two idlers at a time. The idlers are not driven by anything but the belt.

Figure 1.8: Conveyor belts (picture taken at 5 May 2022)

In the photo of figure 1.8 a few conveyor belts are shown. The two belts that are filled with coal are belt 121 and belt 131. On the left a small piece of belt 114 is shown, covered with a sheet metal roof. The load of this belt is protected by the sheet metal and later elevates up towards the silos, which can be seen in the background. The second belt from the left is belt 111. This belt is elevated to transport the load perpendicular onto belt 134. This connection is especially for iron ore loads (which is also why the belt turned orange/ brownish), transporting the load to the iron ore train loader (WB1).

Human workers

There are several human workers working on and around the terminal. There are human workers in the office, in the operating/ control room and on site. During operation hours several workers are **on site**, inspecting the material and cleaning/ repairing where necessary. When going outside, workers need to sign on and off so it is known at all times where the human workers are. If they are about to work on a piece of equipment, this piece will be shut down and fuses are pulled when necessary. These are then secured by locks, so nobody can turn on the equipment by accident. All operations are also communicated by radio, to prevent mistakes and possibly dangerous situations.

In the **control room** there are three operators: A, B and C. They all have different functions. **Operator A** plans the operation and operates the production lines. This operator has contact with everyone on site and has supervision over the entire process. **Operator B** has contact with everyone outside the terminal and works the administration. **Operator C** handles the automated equipment, like stacker reclaimers, train loaders and the sea boat vessel loader (when loading on land). For the automated quay cranes there is another operator; **Operator C2**, but the quay cranes are more often operated manually. The operators also handle the malfunction notifications, whenever one pops up. It is possible to stop, start, or restart the equipment from the control room. They all work with 6 to 8 large computer screens to handle everything they have to operate. The operators have access to the operation processes of all automated equipment and to all cameras on the equipment and on the terminal to help them do their jobs. It takes a lot of time and experience to be able to handle everything in the control room.

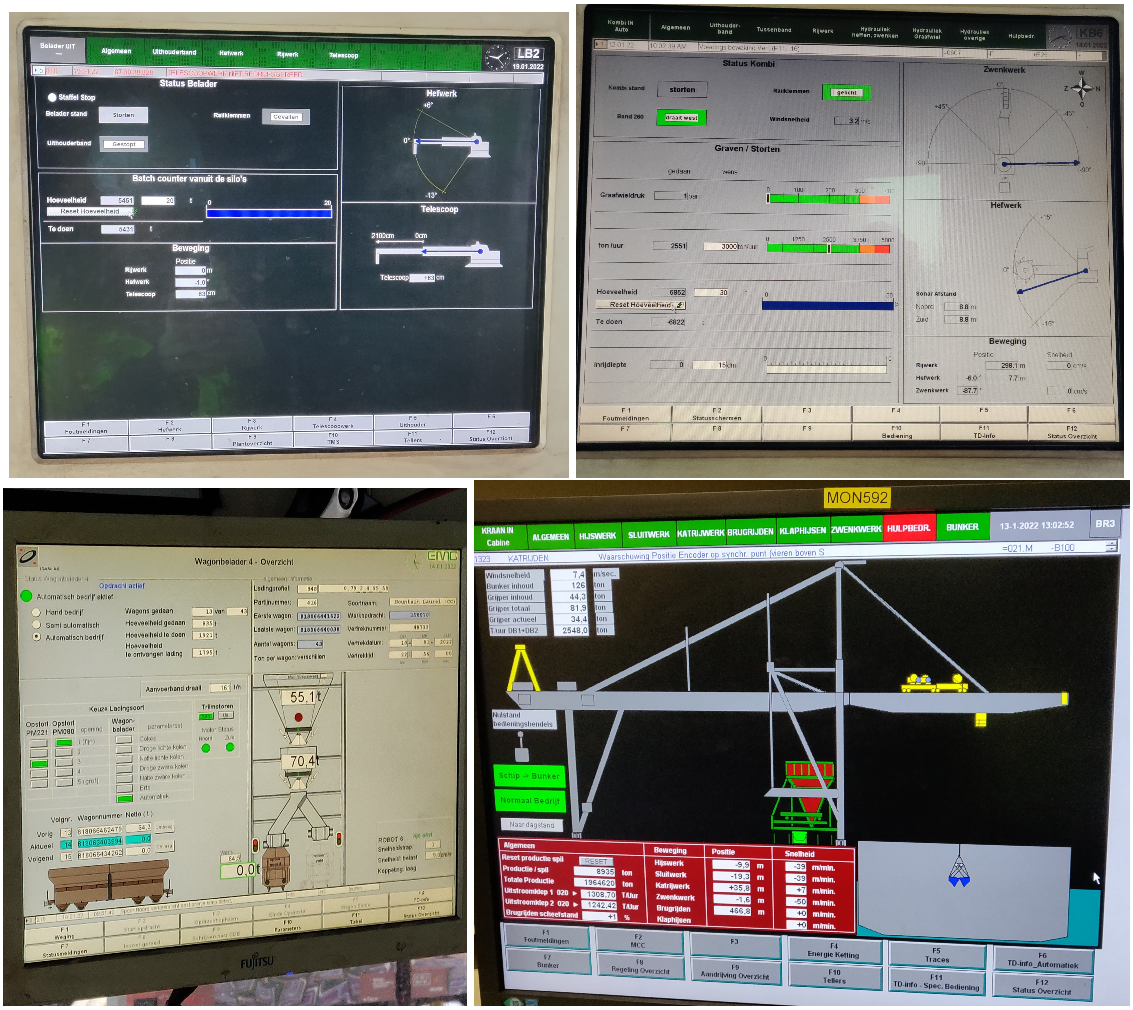


Figure 1.9: Different operating screens for different machines. Left top: barge loader; Right top: Stacker-reclaimer; Left bottom: Train loader; Right bottom: Quay crane (Pictures taken 14 January 2022)

In figure 1.9 a few examples are shown of operating screens for different equipment. In the top left view the operating screen for barge loader 2 is shown. The barge loaders are always operated from the control room. It is possible to travel along the quay with the entire barge loader and to extend the telescope arm. The operator can also put the telescope under a slight angle. The operator can see the the amount of load that is handled.

For the stacker-reclaimer is shown whether it is stacking or reclaiming, whether the belt 260 is traveling West or East, if the brakes are on and the wind speed is shown as well. The pressure on the bucket wheel is shown when the stacker-reclaimer is reclaiming. At the moment the photo was taken, the stacker-reclaimer was stacking with 2551 ton/ hour. The load per hour can be operated on remote or on site. The stacker-reclaimer can travel along the rails, it can rotate 180 degrees and lift in a 30 degree range of motion.

The bottom left view is already shown in one of the previous sections about the train loaders. Here a choice can be made for manual operation, semi-automated or fully automated. The system keeps track of all the wagons of the trains and registers their wagon number. The wagon is weighted before and after loading, while the load is weighted in the bunker as well. This way the train loader can handle the load automatically. The trains are also operated by a robot, which is connected with the train loader system. The system keeps track of all orders.

On the bottom right photo of figure 1.9 the operating screen of a quay crane is shown. On the top left of the screen a few indicators are shown: wind speed, bunker volume, grabber volume, grabber total weight, grabber actual weight and the working load in ton/ hour. On the bottom in red is shown the total production, production per crew, the working load of both outlets and all the parameters (distance and speed in all directions) of the quay crane's position.

In **the office** more human operators can be found handling malfunctions, planning maintenance, ordering parts, looking for new technologies, making sure the equipment is well connected to the database, maintaining the website, maintaining contact with clients, planning orders, etc. This is also the place where clients are met. The client's orders are maintained from the office as well. The database is well maintained by the IT department and others are continuously updating and upgrading the operation processes.

Figure 1.10: Cabin of the stacker-reclaimer for operating manually (Picture taken at 14 January 2022)

1.2. A specified area or piece of equipment for the new maintenance strategy

This section will answer the part of the sub research question *"What area or piece of equipment is most promising to improve its maintenance strategy and why?"* First, the criteria has to be made clear. Some criteria is already stated in the assignment of the TU Delft, or given by the company itself. Other criteria was set up in the initiation phase of this thesis. After a choice has been made, this piece of equipment will be explained in detail and how it is integrated in the dry bulk terminal.

- Availability of condition monitoring data
- Quality of condition monitoring data
- Testing ability
- Applicability to other terminals
- Applicability to other equipment
- Variability in equipment
- Maintainability of the equipment
- Existing malfunctions

The most important criterion will be the use of the existing condition monitoring data, since this is the main part of the original assignment. Therefore it is important to look into the available data, and the quality of the available data. In the initiation phase of this thesis, most data was found on the conveyor belt systems. These systems have the most sensors installed on the terminal. This makes sense, since it is the largest piece of equipment installed on the terminal in terms of quantity and surface.

Besides EMO's own data, there are other companies that use the terminal for testing facilities. Companies like Rulmeca and Küpper (more on that in chapter 3) are testing their condition monitoring equipment on components of the conveyor belt systems (in this case the idlers). This data is available for EMO B.V. and for this thesis.

Conveyor belts are used in lots of other industries as well (food industry, cargo transport, freight handling, pharmaceutical industries), which might make them more standardized overall. The conveyor belt systems in all terminals are made up of the same components like a belt, idlers, drives and tensioners and do not differ much from each other except for sizes.

EMO B.V. is one of the largest dry bulk terminals of Europe and is one of the most innovating dry bulk terminals around the world. EMO B.V. continues to be one of the most modern dry bulk terminals by continuously looking for new solutions and upgrading and innovating the equipment. The terminal is open for new innovations and other companies are able to test at the terminal of EMO B.V. with their new solutions or ideas. This results in being able to work with the newest technologies, but also leads in variety amongst the same equipment. This could mean that some stacker-reclaimers might be more advanced than other stacker-reclaimers. The cranes that are installed on this terminal are quite equal to each other, except that the two older cranes have a smaller capacity (50 ton instead of 85 ton) and the first crane is officially retired after 50+ years of service. However, they are larger and more advanced (the cranes can operate automated or on remote) than cranes used on other dry bulk terminals.

The conveyor belts overall are easy accessible. While larger equipment like quay cranes and stacker-reclaimers might have some spaces that are harder to access, the conveyor belts are mostly close to the ground and have walkways all around. This makes it easier to perform maintenance.

The bigger malfunctions and shutdowns happening during this thesis are all happening around the conveyor belt systems. It would be smart to use these malfunctions for testing the new maintenance strategy and adjusting it if necessary.

The conveyor belt system seems to be the most promising equipment on the dry bulk terminal to investigate its current maintenance strategy and create a new improved maintenance strategy for. Not only because this system is connecting all the equipment on the terminal, it is also the most standardized equipment compared to other terminals. Besides, the malfunctions with larger failure consequences that happened during this thesis, where all malfunctions of conveyor belt systems. The data of these malfunctions can be used to test the new maintenance strategy. In the end, most data was found on the conveyor belt systems as well. Outside companies are willing to investigate in these systems as well, as they are currently testing some of their set-ups at EMO's conveyor belts.

1.3. Conveyor belt systems

Conveyor belts are used in many different industries across the world to transport different product types from one location to another. Conveyor belt systems are used for different product types, which makes the conveyor belt differ in size, speed and even shape for different industries. In this thesis the focus is on conveyor belt systems operating in dry bulk terminals. This section will explain what a dry bulk terminal's conveyor belt system looks like, what its components are and how it works.

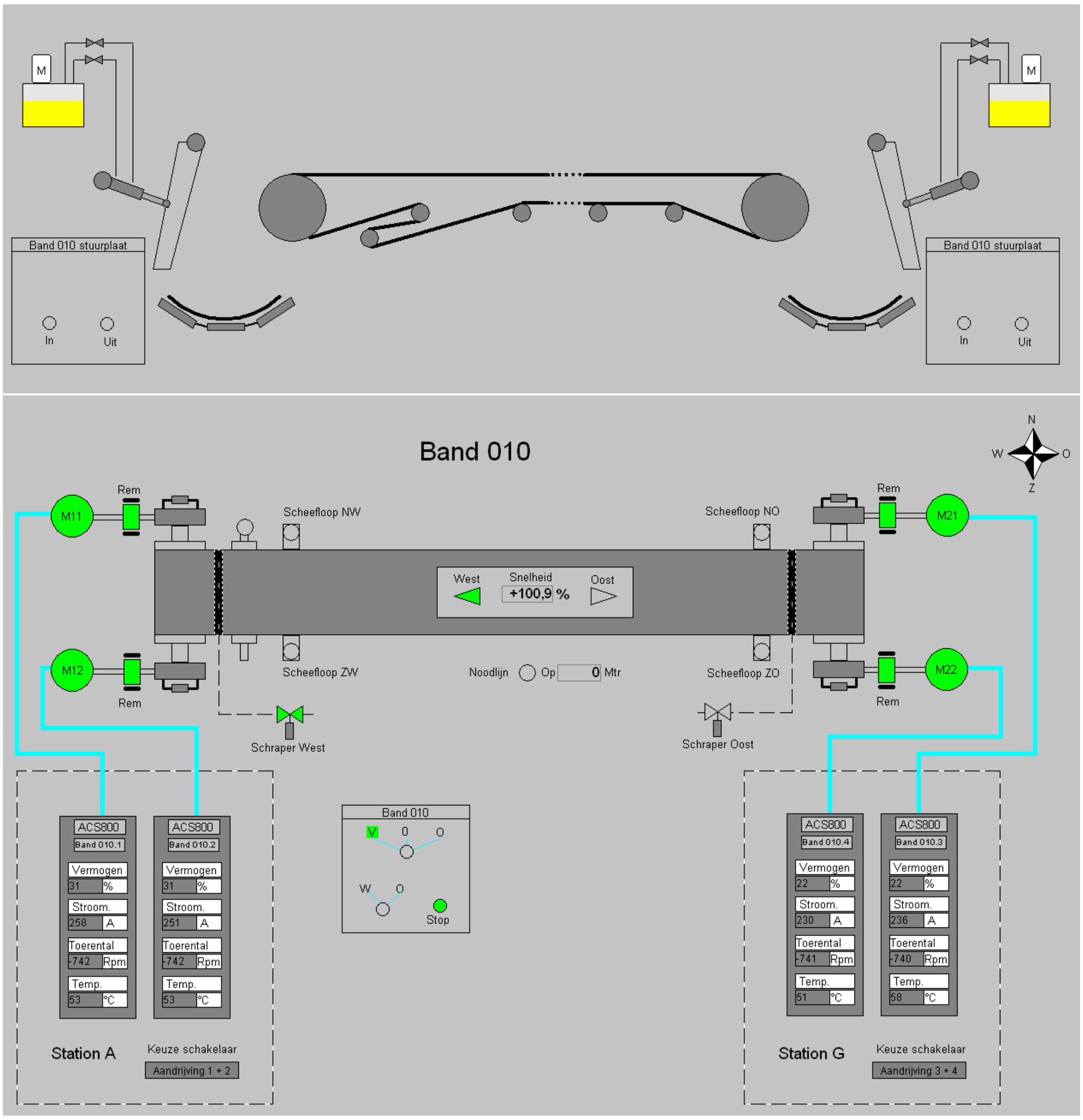


Figure 1.11: Schematic overview of a conveyor belt system [15]

Figure 5.5 shows a schematic overview of conveyor belt system 010. This is the view of a conveyor belt system in general as how it is used at the terminal. The top figure is used for the operation and functioning of the steering plates on the beginning and end of the belt, but it also shows a very schematic layout of this belt conveyor. In the bottom figure the a top view of the conveyor belt is shown with the current variables. Belt speed is shown in percentages, where 100% is equal to 4.5 m/s.

Belt	Length (m)	Width (mm)	Belt	Length (m)	Width (mm)	Belt	Length (m)	Width (mm)
010	2990	1600	**130**	291	1600	**230**	2926	1600
011		1800	**131**	234	1600	**235**	400	1400
014	1013	1800	**132**	229	1600	**240**	2940	1800
020	2832	1600	**133**	163	1800	**240V**	44	2000
030	2826	1600	**134**	52	1600	**250**	2872	1800
040			**135**	380	1400	**252**	66,5	1800
070	890	1800	**136**	186,9	1800	**260**	2785	1800
071	355	1800	**144**	430	1800	**270**	2052	1800
080	2750	1800	**145**	90	1800	**310**	30	1600
100			**146**	362	1800	**314**	521	1800
110			**151**	1113	1800	**330**	84	1800
111	291	1600	**154**	655	1800	**340**	159	1800
112	238	1600	**161**	880	1600	**410**	34,5	1800
113	210	1600	**164**	1335	1800	**420**	62	1800
114	628	1800	**165**	1097	1800	**430**	77,5	1800
114M	16	1800	**171**	1350	1800	**510**	530	1800
115	351	1800	**181**	1571	1800	**520**	521	1800
116	186,5	1800	**182**		1800	**530**	535	1800
117	654	1800	**182M**	16	1800	**610**	39,3	1800
118	506	1800	**210**	3051	1600	**620**	37	1800
119	236	1800	**211**	45	1800	**710**	165	1800
120	300	1600	**214**	127	1800	**711**	344	1600
121	244	1600	**215**	170	1800	**712**	69	1800
122	229	1600	**220**	2944	1600	**720**	165	1800
123	322,7	1800	**221**	218	1600	**721**	344	1600

Table 1.1: Conveyor belts at EMO B.V. with their width and rubber length (EMO B.V. Intranet). Length of the conveyor belt system is a bit less than half the rubber length, because the rubber is looped and makes some extra loops around the winches and tails

Conveyor belt

A conveyor belt system consists of multiple components, of which its main component is the conveyor belt itself. A typical dry bulk conveyor belt is made out of rubber and reinforced with steel. At EMO B.V. the conveyor belts have a total thickness of 20 mm, which is made out of three different layers. The top layer is in contact with the bulk material and experiences the most wear. This layer has a thickness of 10 mm. The second layer is 5 mm thick and is known as the carcass, which is usually made of steel cords in longitudinal direction to increase the overall strength. It is also possible to have a kevlar carcass or to have a carcass made of steel plates instead of cords. For this thesis we focus on the majority of the conveyor belts which are reinforced with steel cords. The third and final layer is also 5 mm thick and is called the tread. This part is in contact with the idlers and drums, therefore it must be clean and may not be contaminated as it must not wear out the drums, pulleys and idlers [67]. The majority of the conveyor belts at EMO B.V. can operate in two directions at a constant speed of 4.5 m/s. As can be seen in table 1.1, most conveyor belts have a width of 1800 mm.

Figure 1.12: Reinforced conveyor belt (the belt is loose and not on tension), belt 151 (Picture taken 29 April 2022)

Drive unit (Electromotor and gearboxes)

The conveyor belts at EMO B.V. can be driven by two different types: frequency controlled drive and a hydrodynamic coupling drive. This thesis will focus on the frequency controlled drive as the hydrodynamic coupling drives will be replaced by the frequency controlled drives [67].

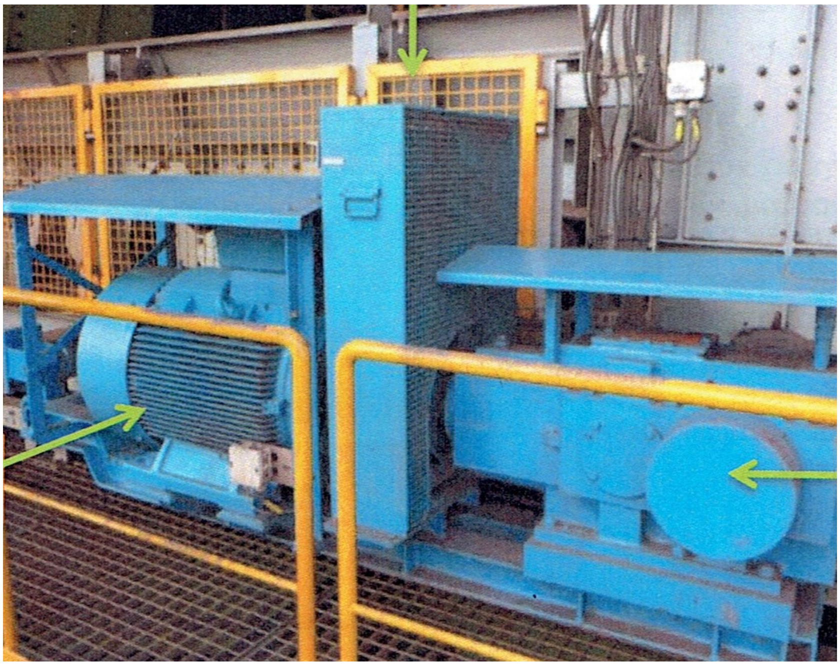


Figure 1.13: Overview of the electromotor drive units of the conveyor belts at EMO B.V. Left arrow points to the electromotor, the top arrow indicates the brake, and the right arrow indicates the gearbox (page 25 [67])

The frequency controlled drive consist of an electromotor (Siemens 355 kW, 4570 Nm, 750 rpm, 500 VD, 50 Hz, 520 A), a gearbox (Flendr 280 kW, 4570 Nm, n1(in) 750 rpm, n2(out) 84.77 rpm, T2N 91.000 Nm nominal torque) and a brake to provide the necessary torque to drive the belt. For short belts only one or two of these drives are required, for longer belts there are more required, mostly four. The drive is controlled by software where parameters like power, force and speed can be monitored. The drive units are located at the head and tail (both ends) of the conveyor belt. For longer conveyor belts this means that two drives are at the head and two at the tail, having four drive units in total. On both ends of the conveyor belt the drive units are working together in a master-slave combination. This means that one of the drives is the master and the other follows. At the other end of the conveyor belt it works the same.

Let's take the 030 conveyor belt as an example. In The West there are two engines (engine 1 and 2, also known as M11 and M12). In The East there are another two engines (number 3 and 4, or also known as M21 and M22). The winch is placed in The East as well. Whenever the 030 is operation in West direction, the tension and load on the belt is the highest in The West. The East has the minor load. Every engine adds tension to the belt exponentially. The winch is programmed to run at a certain value which changes during the operation. This value is called the dynamic set point tension of the winch. To monitor if the winch is actually running at the required speed, its pressure is measured as well.

In figure 1.13 the three parts of the frequency controlled drive units are shown. On the left side there is the electromotor itself, in the middle is the brake and on the right the gearbox is shown. The hydrodynamic coupling drives are outdated and will all be replaced by the frequency controlled drive units.

Idlers

The idlers are supporting the conveyor belt from underneath and move along with the conveyor belt as it travels in longitudinal direction. Different types of idlers are placed at specific locations, depending on their function. The carrying idlers are the most common idlers, which are placed in a trough model where three idlers are placed under a troughing angle as can be seen in figure 1.17. These idlers are smooth and made of steel with a length of 540, 600, or 670 mm, depending on the belt width. The troughing angle and trough model help in keeping the bulk material centered on the belt [67].

Returning idlers are placed underneath the returning conveyor to avoid sagging and collapsing of the returning belt. The returning belt is mostly flat and not troughed, because there is no bulk material on the returning part to be centered. Therefore it is not necessary to place three idlers next to each other under a troughing angle. Often only one idler with a length of 1800 mm or 2000 mm, placed in a flat position, or two rollers with a length of 850 mm or 1000 mm, placed in a V-position are used as returning idlers. These are the same smooth steel rollers as the carrying idlers, but longer and with a thicker axis.

Figure 1.14: The frame and idlers shown without the belt (page 18 [67])

Stutzring idlers (as seen in figure 1.15) are a steel rollers with rubber rings. Only the rubber rings are in contact with the belt. This type of idlers is used for when the conveyor belt travels upwards and is only used for the returning part of the conveyor belt. The stutzring idler comes in the following lengths: 900, 1000, 1800 and 2000 mm. The shorter stutzring idlers are used two at a time in V-position and the longer models are used in flat position.

The polster idler is entirely made of rubber rings and is used at locations where the conveyor belt travels downwards, or where bulk material is dropped onto the conveyor belt. These idlers are also known as heavy duty idlers, because of its ability to absorb impact from the falling bulk material. At EMO B.V. these polster idlers can be found at the exiting part of the stacker-reclaimers close to the bucket wheel and at deposit locations where bulk material is dropped onto the conveyor belt. These idlers come in the following lengths: 530 mm, 600 mm, 670 mm and 1400 mm.

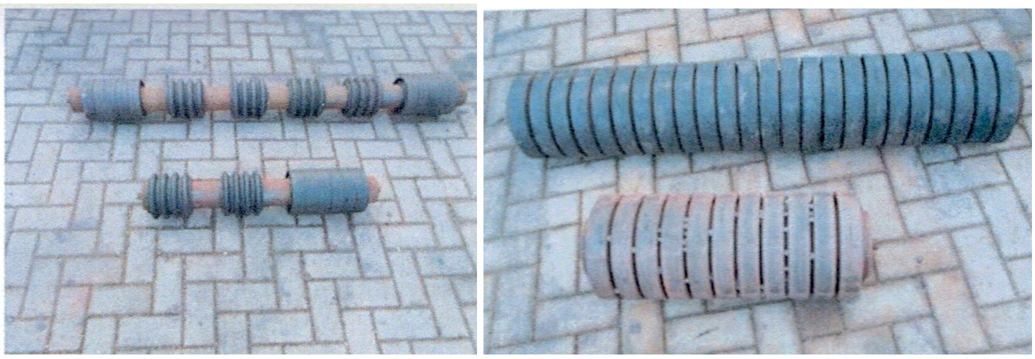


Figure 1.15: Stutzring idlers and Polster idlers(page 31and 32 [67])

Another type of idlers used at the terminal of EMO B.V. is called ”gladstalen uitgebalanceerde rol”, which translates to smooth steel balanced idler. This type is used to weigh the bulk material on the belt. These idlers are placed in a troughing model by three idlers with an individual length of 540 mm, 600 mm, or 670 mm. Underneath the weighing location there are two calibration idlers for calibration of the weighing system. This is done at least once a year, but also when experiencing large deviations.

At some larger deposit points or at locations where spillage must be avoided, the Guirlande idlers (as seen in figure 1.16) come in handy. These garland idlers are made out of five shorter idlers connected by a chain. The garland idlers take the edges of the belt up higher to prevent spillage from the sides. These garland idlers can also be used for more narrow locations as it narrows down the width of the belt by taking up the sides.

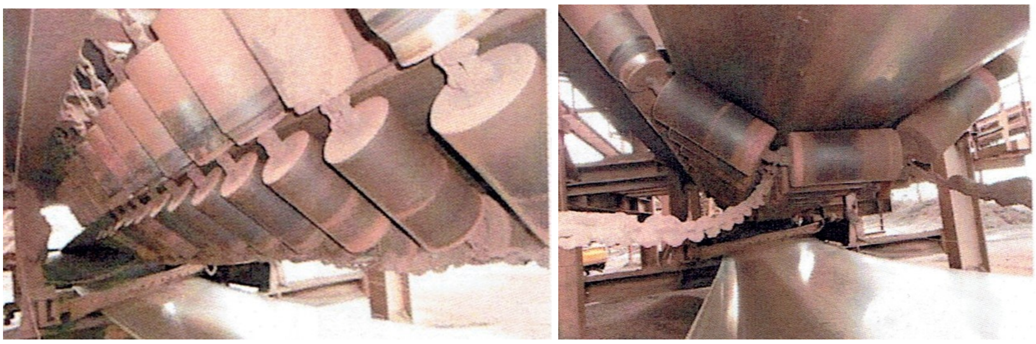


Figure 1.16: Guirlande idlers (page 34 [67])

Negative idlers are placed on top of the returning conveyor belt, close to the returning drum. This helps keeping the conveyor belt in position before entering the return drum.

Another type of idlers used at EMO B.V. is the ”stuurrol”, steering idlers. There are three different types used at the terminal. The oldest steering idler is called a ratchet idler, because it can be set with a ratchet tool. This type is slowly being replaced by one of the following steering idler types. After a while it is almost not possible to apply a new setting of this idler, because of contamination. One of the other steering idlers is called the Tru Trac system, which is fully automated. This idler moves along with the conveyor belt, because of its tapering shape (the thicker part is in the middle). This idler is used for belts that are able to roll in both directions. The last type of steering idler is the hydraulic steering idler. This idler can be used in a one-direction belt, but also in a two-direction belt. This idler is also automated, but instead of a tapered shape, it is made out of two stutzring idlers [67].

All the idler types have their own function, depending on the material type, load capacity, type of conveyor, etcetera. Placing the right idler type at the correct location will help supporting the conveyor belt in the best way possible.

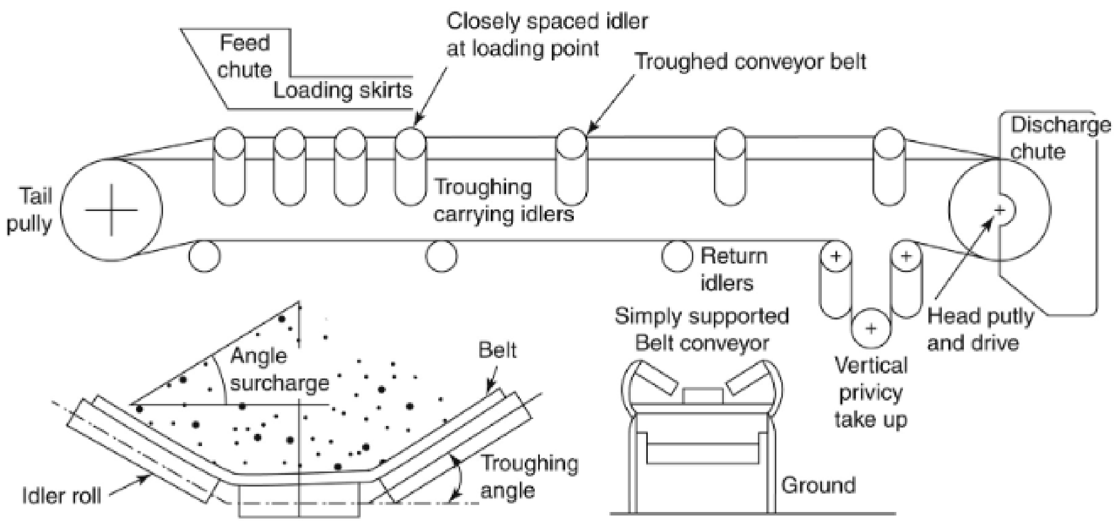


Figure 1.17: A schematic overview of a conveyor belt system [19]

Pulleys

The pulleys are cylindrical drums at the ends of the conveyor belts, carrying and supporting the conveyor belt at the end points. The pulleys are made out of steel and have a rubber coating on top [67].

A driving pulley transfers the required torque from the drive unit to the conveyor belt. These pulleys can be coated with a rubber or ceramic coating, depending on the slippage of the belt experienced earlier. A ceramic pulley is more expensive, but reduces slippage of the conveyor belt compared to a rubber coated pulley. The ceramic pulley is only put at locations where a lot of belt slippage is experienced with a rubber pulley or where the belt will travel also in vertical direction (creating more slippage as well).

Figure 1.18: Pulley (page 38 [67])

The return pulley takes care of returning the belt in the other direction. At EMO B.V. these are only made of steel with a rubber coating. This creates a higher friction between the pulley and conveyor belt. Because of the higher friction there will be some heat generation, leading to wear of the rubber coating on the pulley.

Other pulleys are used for tilting the conveyor belt in another direction while keeping the same operation direction. These pulleys are always covered with rubber. At some locations a tilt pulley (kniktrommel) is placed directly behind a driving pulley to create a greater torque without almost any belt slippage. This set up is used for all new conveyor belts.

A slipping pulley is used to check whether the conveyor belt is running or not. Whenever the belt speed is not correct, it could be that there is a malfunction elsewhere. The belt will then be stopped.

The last type of pulley is the disposal pulley. This one disposes the bulk material from the conveyor belt. These pulleys can be covered with rubber, but can also be not covered at all. When this pulley is also used as a driving pulley it will always be covered with rubber.

Tensioning devices

During take-up and operation a conveyor belt requires a certain amount of tension. Because this amount of tension is different per setting, a tensioning device with variable tension strength is necessary. The tension created by this device can compensate for changes in belt length, caused by difference in load, material, total set up, belt speed, temperature, slippage, or something else. The tensioner is also used for maintenance if a damaged part of the belt has to be detached. Because of different requirements per conveyor belt system and because of technical developments, the terminal of EMO B.V. uses the following tensioning devices at its terminal [67]:

- Automated tensioner
- Hampelman (gravity tensioning device)
- Manual hydraulic tensioner
- Electric hydraulic tensioner
- Static tension wagons

The choice of tensioning device depends on factors such as conveyor length, load variability, and the level of automation desired. Proper tensioning is critical for preventing slippage, reducing wear on the belt and pulleys, and ensuring overall conveyor system efficiency.

Figure 1.19 shows an active or automated tensioning device. This type of tensioner is used for conveyor belts longer than 1100 meters. On the top left the drive winch (motor lier; spanlier aandrijving), brake (rem), and gearbox of the winch (TWK lier; spanlier aandrijving) are shown. On the right the drive unit (band aandrijving) and drum or pulley (aandrijftrommel) of the belt are shown with the wagon (wagen) that can move along the rails (rails). The cables (lierdraden) move together with the wagon. The pressure box (drukdoos) handles the pressure that is used for operating the belt. The pressure is usually between 160 and 180 bar for starting the belt and between 110 and 130 bar during normal operation.

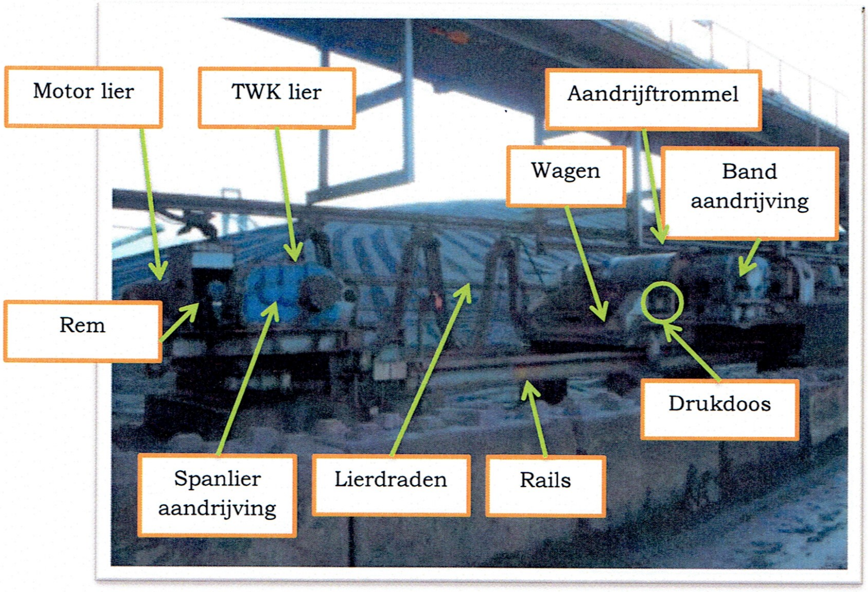


Figure 1.19: Active or automated tensioning device (page 43 [67])

The Hampelman tensioner (as shown in figure 1.20) is a gravity driven tensioner, also known as an inactive tension wagon. This particular tensioner is used for conveyor belts shorter than 700 meters. It consists of a counterweight (contragewicht), two tilt pulleys (kniktrommel), a return pulley (keertrommel), and a guidance (geleider) for the counterweight. The device is surrounded by a cage to ensure safety for human workers, but also to be still able to clean the device. During take-up the counterweight is pulled upwards and when the belt is at its full speed, the counterweight will lower. The biggest disadvantage of this tensioning device is that the overall tension can only be varied by removing or adding weight to the counterweight.

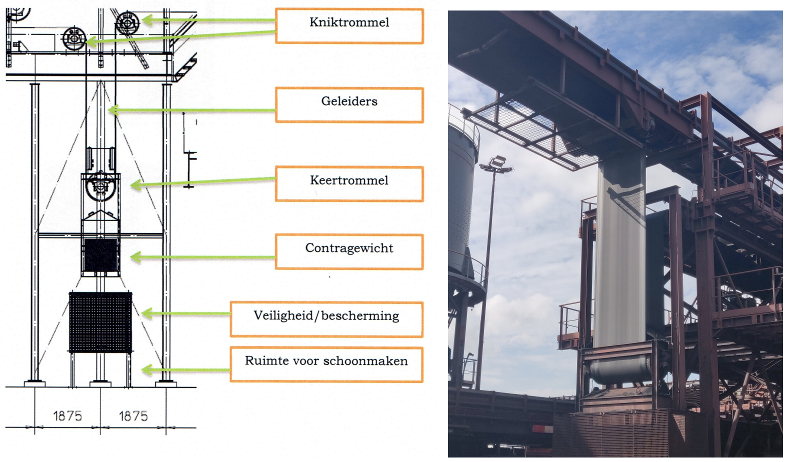


Figure 1.20: Hampelman tensioner; schematic overview (page 45 [67]) and in real life (picture taken at 14 September 2022)

A manual adjusted hydraulic tensioner is - as the name suggests - manually operated. In figure 1.21 a manual adjusted hydraulic tensioner is shown. A pressure gauge shows the amount of pressure, which normally is around 100 bar. This tensioning device consist of a tension wagon (spanwagen), one or two hydraulic cylinders (cilinder), a pump (po,punit) and a lever to manually adjust the pressure. The electrical adjusted hydraulic tensioner works similar, but is operated electrically instead of manually.

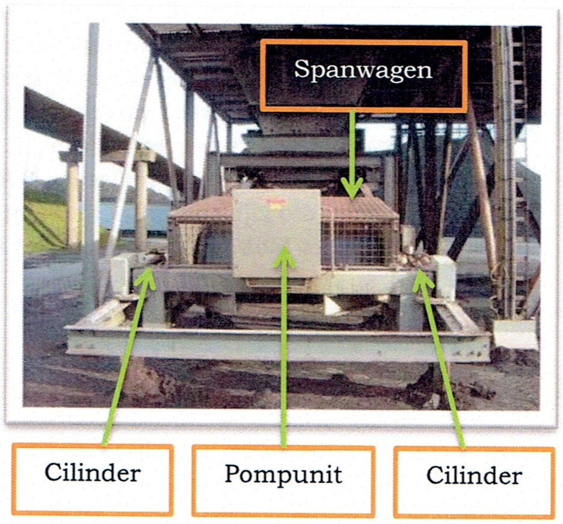


Figure 1.21: Manual adjusted hydraulic tensioner (page 47 [67])

Static tension wagons work similar to gravity tensioners (the Hampelman) with a counterweight. But instead of cylindrical pulleys, plate pulleys are used. As EMO B.V. keeps developping its own devices, these static tension wagons might all be slightly different from each other because of continuous improvements. In figure 1.22 a static tension wagon is shown, where the green arrow in the left picture addresses the counterweight and the green arrow in the right picture shows the return pulley.

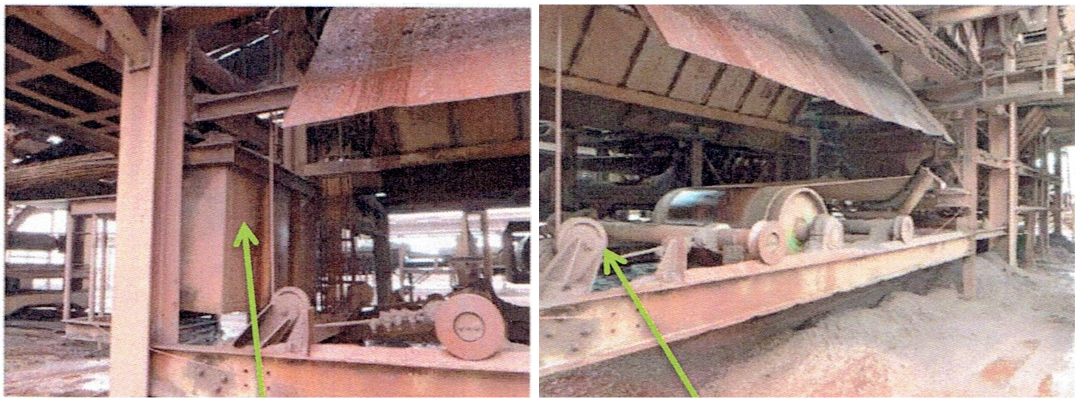


Figure 1.22: Static tension wagon components (page 49 [67])

1.4. Conclusion

"What is EMO B.V. and what equipment in installed? What area or piece of equipment is most promising to improve its maintenance strategy and why?" EMO B.V. is one of the largest and most modern dry bulk terminals of Europe with a total surface of 170 hectares [14]. Unloading vessels is done by five quay cranes, of which three 85 ton and two 50 ton cranes. Loading vessels is done by three barge loaders, one sea-going vessel loader and three train loaders, of which one is specifically suited for iron ore. The almost 8 million ton storage area is operated by seven stacker-reclaimers which can be operated manually or automatically. Over 27 kilometers of conveyor belts are installed on the terminal to transport the dry bulk material around the terminal and between equipment.

The equipment on the terminal of EMO B.V. is connected by conveyor belts. These systems consist of a driving unit, a rubber belt reinforced with steel cables, a large amount of idlers to carry the belt and the dry bulk material, a steel framework, drums and pulleys and a winch or tensioner device to put the correct amount of tension on the belt. The belts are remotely operated from the control room and lots of data is gained from all the sensors around the conveyor belt systems. This data will be discussed in the following chapters.

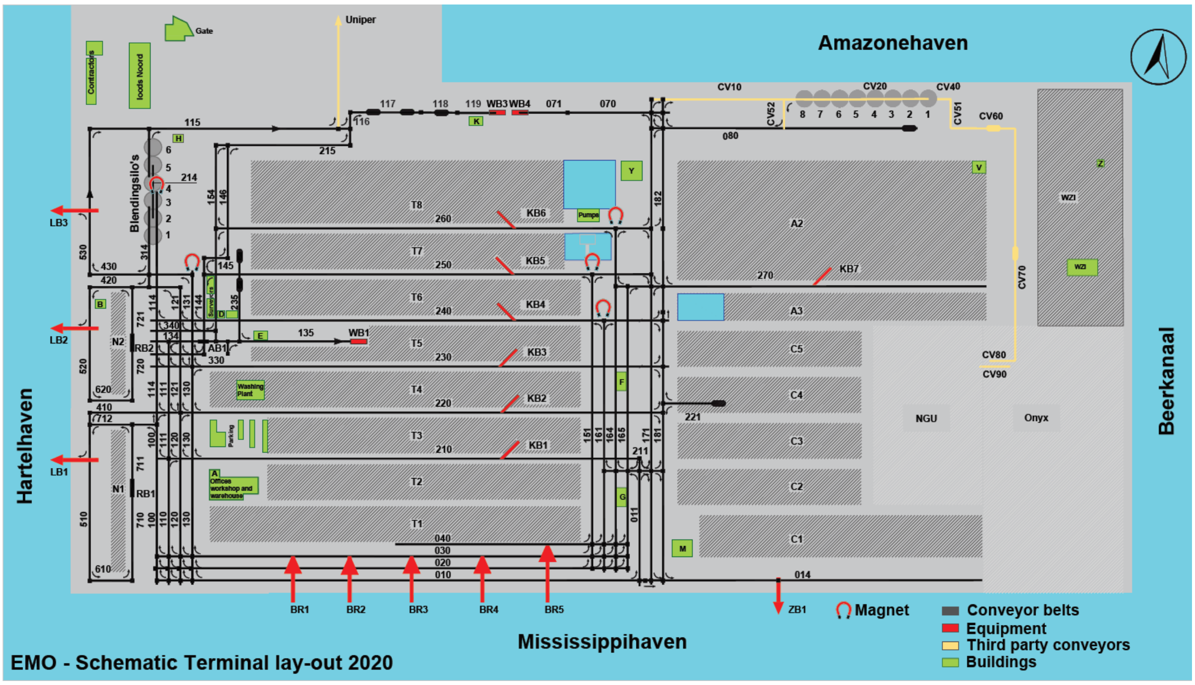


Figure 1.23: Schematic lay-out of the EMO terminal 2020 (Intranet)

The conveyor belt systems will be investigated because this is the connecting factor between all operating systems and machines. Without conveyor belts, the terminal would not be able to operate. Besides, there is some investigation and testing already in operation on the terminal. This makes it possible to use these solutions and investigate in improvements and these solutions can also be used as examples for new solutions.

From all the equipment on the terminal, conveyor belts are the most standardized equipment compared to other terminals. The gained data from the initial phase of this thesis was mainly data from conveyor belt systems. The conveyor belts are easily accessible for maintenance, while other equipment is larger and might be harder to maintain because of worse accessibility.

The bigger malfunctions and shutdowns happening during this thesis also ask for solutions for conveyor belt systems. Together, this concludes this chapter in choosing conveyor belt systems as the main subject to be investigated for a new maintenance strategy based on existing condition monitoring data.

2
Condition monitoring and maintenance techniques

This chapter will answer the sub research question *"What is condition monitoring and what are different maintenance strategies? What is EMO's current maintenance strategy?"*. The first section will be part of a literature study, explaining condition monitoring as well as its benefits and disadvantages. The second section will be another part of a literature study, searching for existing condition monitoring techniques in dry bulk terminals (in patents and international standards). The third section will explain the different maintenance strategies, where the fourth section will explain the current strategies at EMO B.V. The fifth section explains the problem statement and how there is room for improvement. The last section will conclude this chapter.

2.1. Condition monitoring in general

Condition monitoring is a method where data from equipment is regularly or continuously collected and analyzed to assess the equipment's performance and identify potential issues and/ or abnormalities. Condition monitoring consists of measuring equipment parameters to identify a significant change which indicates a developing fault or malfunction. When such a fault or malfunction is detected, continuing operation under normal circumstances could shorten the lifespan of this piece of equipment. With condition monitoring it is possible to address such a fault or malfunction in an early state and prevent this fault or malfunction developing into a major failure or breakdown. In addition to preventing malfunctions from developing into a major failure or breakdown, condition monitoring has proven to be beneficial in maintenance scheduling, reducing downtime, reducing costs, and increasing equipment reliability and safety [69, 1, 33].

According to S.K. Nithin et al. [12] condition monitoring is the process of measuring instrument parameters, such as machine motion, temperature, oil condition, while paying attention to visible changes that can suggest impending errors. With trend monitoring the measured data is interpreted to determine when the equipment deteriorates beyond a critical threshold. Trend monitoring requires the analysis of the trend of a certain parameter that can be measured which indicates the deterioration of the equipment. For example: tracking engine data of airplanes to detect irregularities in engine performance to avoid more expensive damage.

ISO 13372 and NEN-ISO 13372 [5] define condition monitoring as follows: *"Condition monitoring is the acquisition and processing of information and data that indicate the state of a machine over time. The machine state deteriorates if faults or failures occur."* Its activities should be directed toward identifying and avoiding root cause failure modes [4]. For condition monitoring, certain parameters of a component, machine, or equipment are measured, and this data are collected, transmitted, translated, and processed with software. This data can be used for the indication of failure by finding irregularities in the data.

Parameters that are measured for condition monitoring include (but are not limited to) vibration, temperature, flow rates, contamination, power, tribology (oil analysis), and speed. These parameters are typically associated with performance, condition, and quality criteria and form the base of the evaluation of a component's or machine's function and condition [5]. The parameters are measured with a variety of sensors and sent to the computer software by a data acquisition device, also known as a DAQ device. The computer software will translate and analyse the data so human workers can ”read” the condition of the component or machine. Whenever the parameters show an irregularity, this could be an indication of a malfunction or failure. When saving historical data, patterns can be recognized to - eventually - prevent failure. This way, condition monitoring forms the base for condition-based and predictive maintenance.

Condition monitoring techniques

Different parameters can be measured for condition monitoring. Therefore, different condition monitoring techniques exist. The following table will summarize the most useful condition monitoring techniques for this thesis:

Condition monitoring technique	Measures	Detects/ used for	Examples
Vibration analysis	Vibration/ displacement	Imbalance, misalignment, bearing wear, gear tooth issues	Shock pulse analysis, Fast Fourier analysis, time waveform analysis, spectograms
Ultrasonic monitoring		Leaks, cavitations	
Thermography	Temperature	Imbalances, wear, stress, misalignment	Infrared thermography
Tribology	Lubricant quality	Wear, overheating, contamination	Ferrography, spectroscopy, water presence, viscosity
Radiography		Internal defects like corrosion, welding flaws	
Laser interferometry	Displacement	Corrosion, cavities, cracks	Laser shearography, laser ultrasonics, strain mapping
Electrical monitoring	Induction, capacitance, frequency and pulse response, degradation	Imbalance, faults	Megohmmeter, dielectric withstand test, power signature analysis
Electromagnetic monitoring	Magnetic field distortions	Cracks, dent, corrosion, weaknesses	Eddy-current testing, magnetic flux leakage, metal magnetic memory
Motor circuit analysis	Condition of electromotor	Coupling, power quality, condition of rotors	
Acoustic	Acoustic emissions	Early detection of faults	
Pressure monitoring	Pressure	Overloading	
Wear debris			

Table 2.1: Several condition monitoring techniques found in literature studies

Requirements for condition monitoring in general

Condition monitoring measures the equipment's parameters to identify upcoming failure. Some key indicators for condition monitoring will be explained in this subsection. First of all, to measure any parameter, a sensor is required. There can be multiple sensors to measure several parameters. Data gained from these sensors must be translated so it can be read by humans or computers. A data acquisition device is used to convert this (analog) sensor data to a readable (digital) input for the computer software. This input can be filtered or amplified to improve the data quality. These two methods are examples of a technique called signal conditioning and is done when the sensor output is difficult to read (e.g. noise in data or low leveled data). A more thorough description of data acquisition is given in appendix E, which was part of the literature assignment.

After data acquisition and communication, the obtained data must be analysed. This can be done by a computer using various techniques, including statistical methods, signal processing, and machine learning. By analysing data it is possible to recognize patterns and indicate abnormalities, which could lead to a potential fault or malfunction in the equipment. When an abnormality is detected, the system continues with fault detection and diagnostics to protect the equipment from more harm if necessary.

Fault detection and diagnostics is a proactive approach where faults are detected in an early state. The fault diagnostics decides whether immediate maintenance is required or other corrective actions to minimize the risk of malfunctions and damage to other components. This decision making is used for predictive maintenance where the equipment is continuously monitored and only maintained when required and not based on a time- or cycle-based schedule. The maintenance strategy is ”predicted” by the condition monitoring techniques.

Implementing condition monitoring

Utne et al. [36] talks about a decision support model for condition monitoring methods. In their proposal, the process of condition monitoring can be divided into three main steps:

- **Step 1:** Analysis and selection of critical equipment
- **Step 2:** Analysis and mapping of condition monitoring methods
- **Step 3:** Assessment and decision-making

The first step is to decide what equipment must be monitored and what parameters will be measured. This step also includes installation of sensors and instruments to get the actual data. The data must be collected, translated and communicated as was described in the previous subsection. The required instruments for this (e.g. data acquisition device, software, computer) must be installed.

In the second step the obtained data will be analysed. This analysis includes recognizing patterns in the data and indicating abnormalities. Several condition monitoring methods can be used for obtaining different sets of data or even for the same kind of data, to rule out faulty sensors. This step also includes fault detection and diagnostics. Thresholds and alarms can be programmed to alert the system of a faulty situation.

The final step is to decide what action to take when a malfunction is detected. Is it safe to continue operation, or is it necessary to stop the operation immediately and only continue after maintenance? It is possible that continuing operation at normal circumstances will cause more damage. This could be damage to other components or to the equipment itself. Both events must be prevented if possible. The decision making step decides what option is best. This decision making is based on previous events, experience and testing. Of course it is possible that new malfunctions will not be detected in an early state, therefore the fault detection and diagnostics - as well as the decision making - must be improved and kept up to date continuously.

Benefits

Condition monitoring has lots of benefits like increased safety, reliability, availability, and improved machine performance. Since condition monitoring is about checking the equipment’s condition, failures and malfunctions can be recognized in an early state. Therefore, condition monitoring also could lead to a decrease in maintenance costs and a decrease in unplanned downtime. With condition monitoring, maintenance can be done according to the equipment’s condition, instead of on a schedule made on beforehand. This will be explained in the next section as well, where the different maintenance techniques will be discussed. The main benefits of condition monitoring include:

- Early fault detection
- Optimizing maintenance planning
- Reduce downtime
- Reduce maintenance cost
- Improve reliability and operation
- Improve safety
- 24/7 inspection
- Real-time data

Unfortunately condition monitoring also comes with some disadvantages:

- Implementation cost
- False alarms
- Large data warehouse
- Expertise

When implementing condition monitoring, there must be made an investment in sensors, data acquisition devices, software and training. Human workers must be trained to work with condition monitoring tools and to maintain the equipment and software. It also cost some time and employees to install the entire set-up. In the case of this thesis, there is an existing condition monitoring base for the conveyor belt systems. There is a large data warehouse where all sensor data is save at 10 Hz. This data is kept for an average time of two weeks before this is renewed.

There is a possibility that the condition monitoring software will give a false alarm. This can be because of a faulty sensor, or because of a fault in the software, or even a crash. Faulty sensors can be detected by several methods, but this will also cost time and money to set-up.

A certain level of expertise is required to work with all the condition monitoring software and to be able to read the data. While the software is supposed to translate the raw data into readable data, employees must have some knowledge of the shown parameters. Normal values or ranges of values must be known or must be implemented in the software.

2.2. Existing condition monitoring techniques for conveyor belt systems in literature

This section will briefly discuss the existing condition monitoring techniques that are currently patented or used in other dry bulk terminals around the world. Several international and Dutch standards for condition monitoring (in conveyor belts or components of conveyor belt systems) are described as well.

Patents

This section describes the patented monitoring techniques for dry bulk terminals. Some of the patents are old and not used anymore, but could be interesting to look into.

US3742477A Conveyor belt condition monitoring apparatus [1973] *(Right cessation due to non payment of renewal fees)*

Goodyear developed an apparatus to monitor the condition of an electrical conductor, which is associated with a moving conveyor belt to provide a fail-safe indication of the belt's condition. This apparatus consists of a detector circuit which includes an oscillator with magnetically coupled coils. The conveyor belt contains conductors. The position of these moving conductors compared to the magnetically coupled coils of the oscillator results in a change in the oscillator's output. This is an indication of the condition of the belt by means of tears and other damage and a signal will be provided to an indicator circuit to shut down the power of the belt drive unit in the case that the belt is in an unsafe condition [29].

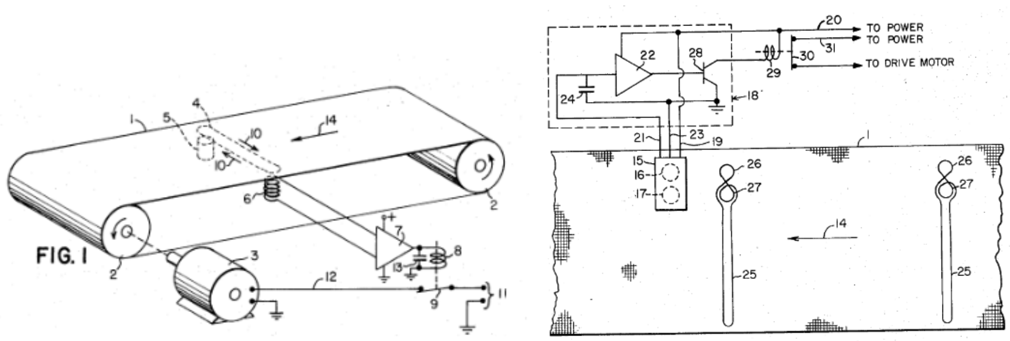


Figure 2.1: Drawings from patent US3742477A [29]

Since the renewal fees were not paid, the patent is usable. Unfortunately this will only work for non-reinforced conveyor belts. At the terminal of EMO B.V. only reinforced conveyor belts are used to carry the impact and weight of the dry bulk material. The reinforced belts will interrupt the outcome, since the outcome is based on the magnetic feedback of the conductors placed on the belt.

DE19532010A1 Monitoring condition of transverse reinforced conveyor belt [1997] *(Right cessation due to non payment of renewal fees)*

This system monitors the condition of reinforced (wired with steel cords) conveyor belts. When the conveyor belt is running, it produces sound. A sensor in the conveyor carrying frame detects the sound level and compares it to specified threshold values. When the sound level exceeds a limit value, the drive of the conveyor belt is stopped [35].

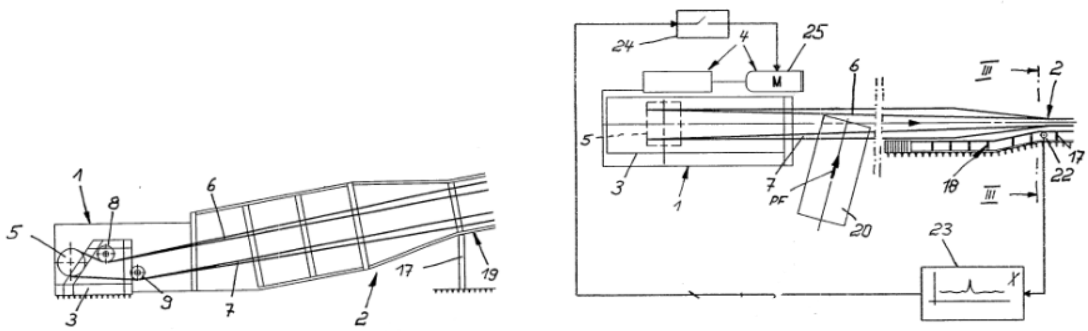


Figure 2.2: Drawings from patent DE19532010A1 [35]

Because the owner of this patent did not pay his renewal fees, the patent is free to use. Unlike the first patent, this one is made for reinforced conveyor belts. The patent is based on the sound that is made by the belt. This sound is measured and then compared to some limit values. Measuring only the sound coming from the belt is very difficult, since the idlers and bearings tend to make more noise than the belt itself. Especially when an idler has a flat side or when a bearing is loose or damaged, the faulty idler produces loud noises that will interrupt the sound measurement. This technique will not be likely to work in a setting that is used nowadays at the terminal of EMO B.V. or at any dry bulk terminal of that matter.

US2012168281A1 Conveyor belt condition monitoring system [2012]

This conveyor belt monitoring system uses multiple sensors (coils, RFID, and Hall Effect sensors) to measure magnetic disruptions of the belt's steel cords to indicate splice joints, rip panels, and reinforcing cord damage. After measuring, the data is collected to chart belt wear and damage trends. The signal is communicated through a PLC-based control system and compared to predetermined thresholds. When these predetermined thresholds are exceeded, the system will stop the belt to prevent belt failure [61].

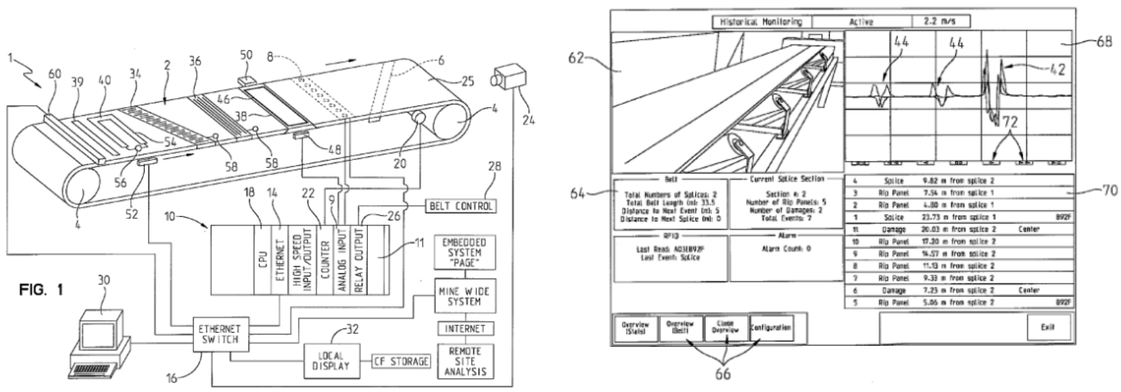


Figure 2.3: Drawings from patent US2012168281A1 [61]

This patent is fully based on the condition of the steel cords inside the belt. It does not show belt damage if the steel cords inside are not damaged in any way. Magnetic disruptions are measured to indicate this damage. The coils, RFID and Hall Effect sensors are all based on the electromagnetic response of the reinforced belt. This patent has a good technique for measuring damage to the steel cords, but not so much for measuring damage on the rubber that has not (yet) damaged the steel cords below.

US2013077743A1 System for the non-destructive inspection of a conveyor belt via high-energy radiation [2013]

The conveyor belt has a cover on the carrying and backing side, made of elastomeric material and embedded tension members. During operation, the conveyor belt is guided through a housing, where a radiation source emits high energy rays through the belt's surface. A sensor on the other side of the belt detects the rays which are passing through the belt and sends a signal to a processor, which evaluates the result and stops the belt if exceeding a predetermined value [58].

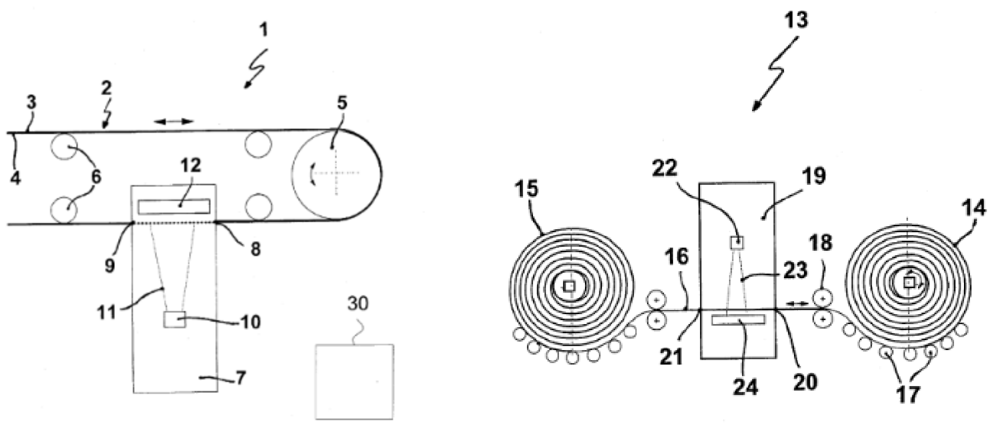


Figure 2.4: Drawings from patent US2013077743A1 [58]

This patent makes use of a housing around the returning conveyor belt. The idea behind it might work. In practice the returning belt is always dirty of residual bulk material. For this patent to work, the belt must be cleaned thoroughly before entering the housing. Otherwise residual material could be mistaken for dents or damage on the belt.

US2013129042A1 Apparatus for monitoring the connection of a conveyor belt by means of high-energy rays [2013]

The conveyor belt is guided through a housing (on the lower part of the conveyor belt) with a sensor and a radiation source which emits high energy rays in the direction of the belt surface, while the belt is running. The rays that have passed through the belt are detected by a sensor, after which a process computer will evaluate the result by comparing the actual connection values to set and limit connection values. Once the measured value is exceeding the limits the drive of the conveyor belt is stopped by the software [57].

This patent is very similar to the previous patent, therefore similar in judgement.

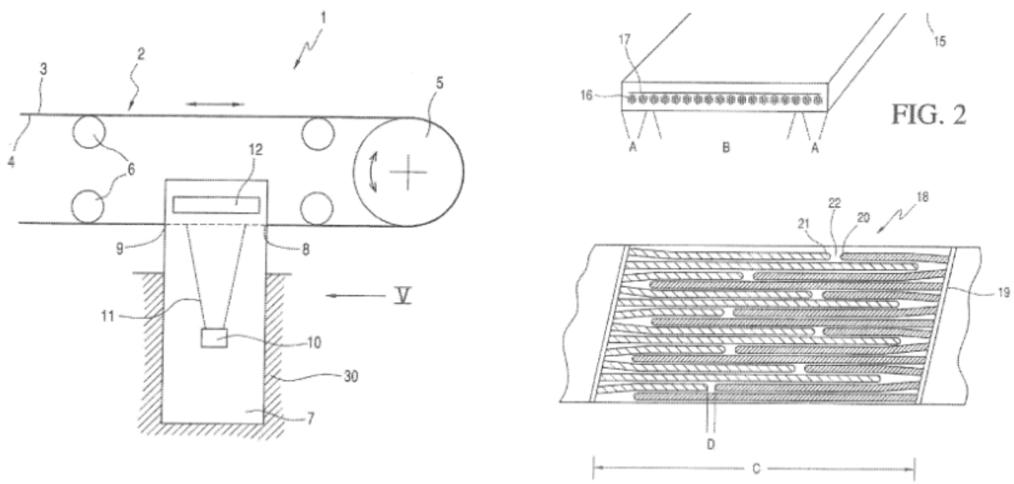


Figure 2.5: Drawings from patent US2013129042A1 [57]

International standards

Standard	Name	Part
ISO13372	Condition monitoring and diagnostics of machines Vocabulary	
ISO13373-2	Condition monitoring and diagnostics of machines Vibration condition monitoring	Part 2: Processing, analysis and presentation of vibration data
ISO13373-3	Condition monitoring and diagnostics of machines Vibration condition monitoring	Part 3: Guidelines for vibration diagnosis
ISO13373-9	Condition monitoring and diagnostics of machines Vibration condition monitoring	Part 9: Diagnostic techniques for electric motors
ISO13374-1	Condition monitoring and diagnostics of machines Data processing, communication and presentation	Part 1: General guidelines
ISO13374-2	Condition monitoring and diagnostics of machines Data processing,communication and presentation	Part 2: Data processing
ISO13374-4	Condition monitoring and diagnostics of machines Data processing, communication and presentation	Part 4: Presentation
ISO13379-1	Condition monitoring and diagnostics of machines Data interpretation and diagnostics techniques	Part 1: General guidelines
NEN-ISO13381-1	Condition monitoring and diagnostics of machines Prognostics	Part 1: General guidelines
ISO14830-1	Condition monitoring and diagnostics of machines Tribology-based monitoring and diagnostics	Part 1: General requirements and guidelines
ISO17359	Condition monitoring and diagnostics of machines General guidelines	
ISO18129	Condition monitoring and diagnostics of machines Approaches for performance diagnosis	
ISO18434-1	Condition monitoring and diagnostics of machines Thermography	Part 1: General procedures
ISO18434-2	Condition monitoring and diagnostics of machines Thermography	Part 2: Image interpretation and diagnostics
ISO18436-3	Condition monitoring and diagnostics of machines Requirements for qualification and assessment of personell	Part 3: Requirements for training bodies and the training process
ISO22096	Condition monitoring and diagnostics of machines Acoustic emission	
ISO29821	Condition monitoring and diagnostics of machines Ultrasound	General guidelines, procedures and validation
NEN-EN50518	Monitoring and alarm receiving centre	
IEC60812	Failure modes and effects analysis (FMEA and FMECA)	

Table 2.2: International standards that were part of the literature studies of this thesis

ISO13372 is the international standard for machine condition monitoring and diagnostics. This specific standard gives a vocabulary that is used in the following international standards [5].

ISO13373 is the international standard for machine vibration condition monitoring and diagnostics. Part 1 describes general procedures [3]. Part 2 (processing, analysis and presentation of vibration data) of this international standard recommends procedures for processing and presenting vibration condition monitoring data. It also recommends procedures for analyzing vibration signatures and performing diagnostics [51]. This part of the international standard focuses on two basic approaches for analysing vibration signals: the time and the frequency domain. Part 9 (diagnostic techniques for electric motors) specifies procedures for vibration diagnostics of electric motors. This part covers four motor types: squirrel cage induction, wound-rotor instruction, salient-pole and DC motors with a power higher than 15 kW [52].

ISO13374 is the international standard for data processing, communication and presentation of machine condition monitoring and diagnostics. The standard is divided into several parts, also shown in table 2.2. The first part (general guidelines) establishes general guidelines for software specifications [42]. The second part (data processing) describes the requirements for a reference information model and reference processing model in detail. These models are required to adequately describe all data processing elements [43]. The third part is all about data communication. The fourth part (presentation) describes the requirements to present the information for technical analysis and decision support for condition monitoring and diagnostics [44].

ISO13379 is the international standard for data interpretation and diagnostics techniques of machine condition monitoring and diagnostics. Part 1 describes the general guidelines for the data interpretation and diagnostics of machines. This standard covers the industrial machinery, such as turbines, compressors, pumps, generators, electrical motors, blowers, gearboxes and fans [4].

NEN-ISO13381 is the Dutch standard derived from the international standard ISO13381: Prognostics of machine condition monitoring and diagnostics. Part 1 describes the general guidelines for this international standard and it provides guidance for the development and application of prognosis processes [72].

ISO14830 is the international standard for tribology-based monitoring and diagnostics. Tribology is the science of understanding friction, lubrication and wear phenomena for interacting surfaces in relative motion. The first part covers general requirements and guidelines for the analysis of lubricating oils, hydraulic fluids, synthetic fluids and greases [49].

ISO17359 is the international standard for guidelines on general procedures for condition monitoring and diagnostics of machines. This international standard gives guidelines for setting up a condition monitoring program. For more specific machine related processes, this standard will refer to the other standards in condition monitoring and diagnostics [45].

ISO18129 is the international standard for approaches for performance diagnosis of machine condition monitoring and diagnostics. It provides guidelines to apply performance monitoring and diagnostics. Terminology is explained as well as the different types of performance monitoring and diagnostics [41].

ISO18434 is the international standard for thermography of machines for condition monitoring and diagnostics. Part 1 of this international standard describes general procedures for infrared thermography. This standard covers machinery such as valves, fluid and electrically powered machiens, and machinery related heat exchanger equipment [47]. Part 2 provides guidence for the interpretation of infrared thermograms [48].

ISO18436 is the international standard that describes requirements for qualification and assessment of personell in the machine condition monitoring and diagnostics section. Part 3 of this international standard sets requirements for training bodies and the training process [46].

ISO22096 is the international standard for acoustic emission techniques of machine condition monitoring and diagnostics. This standard covers structure-borne measurements only [40].

ISO29821 is the international standard for ultrasound techniques in machine condition monitoring and diagnostics. Part 1 describes the general guidelines, procedures and validation. This applies to both airborne and structure borne ultrasound [50].

NEN-EN50518 is the Dutch national standard which is derived from the international standard ISO50518: Monitoring and alarm receiving centre. This national standard specifies the minimum requirements for monitoring, receiving and processing of alarm messages which are generated by alarm systems. Requirements are given for category I and II of the alarm receiving centres [6].

IEC60812 is the international standard for failure modes and effects analysis (FMEA and FMECA).

The variant FMECA is short for failure modes, effects and criticality analysis. This international standard explains how an FMEA and an FMECA are planned, performed, documented and maintained. The purpose of the analysis is to establish how processes or products might fail to perform so that any required treatments could be identified [39].

2.3. Maintenance strategies in general

This section will explain the basics of the most common used maintenance strategies: run-to-failure maintenance, preventive maintenance, condition based maintenance, and predictive maintenance. The following section will explain which maintenance strategies EMO B.V. currently uses.

New machines or components tend to have a high probability of failure in the first part of time, due to possible installation issues. This part of time is called the ”start up” period, as can be seen in the bathtub curve of figure 2.6. Followed is a period of ”normal life” where the machine or component has relatively low failure and functions properly. After this period, the probability of failure increases with time, because the equipment is worn out and on the end of its life [64].

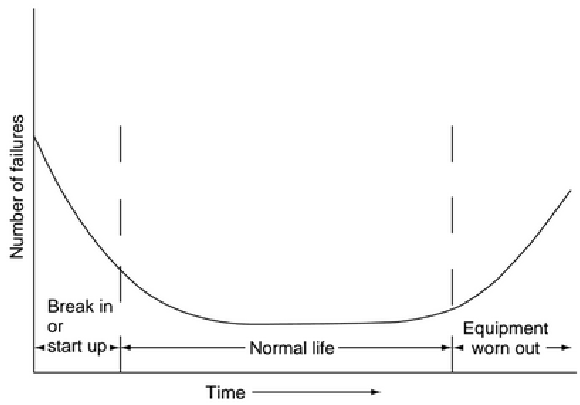


Figure 2.6: Bathtub curve [64]

There are several types of maintenance. Since this thesis focuses on the state-of-the-art solutions on a dry bulk terminal, only the most common types of maintenance will be described in this section [55] [34] [63]. Isermann [53] states that:

> *”Maintenance is understood as an action taken to retain a system in, or return a system to its designed operating condition. It extends the useful life of systems, ensures the optimum availability of installed equipment or equipment for emergency use.”*

Run-to-failure maintenance

Run-to-failure maintenance is a reactive management technique that waits until failure before taking any maintenance action. When a component fails to operate, it will be fixed. With this strategy there is no money spend on any (unnecessary) maintenance or checks before failure occurs. This does not mean that this is the cheapest maintenance strategy, it tends to be one of the most expensive maintenance strategies because of its side effects [64] [68].

The run-to-failure maintenance strategy is accompanied by some negative effects and expenses. When a machine breaks down, this must be replaced or repaired. This means downtime; this specific machine is not able to operate. To fix this machine as fast as possible, there might be extra labor cost spent for paying overtime or for hiring extra personnel. To make this maintenance strategy work without excessive downtime, it is required to have spare parts of all major components available. This on itself requires storage and warehousing, also leading to higher expenses.

For some components it makes sense to run with the run-to-failure strategy. This might be because these components are hard to monitor, or it might be more expensive to monitor these components compared to replacing them. It is also possible that these components are small and therefore easy to store in a warehouse. Parts with short lifetime expectancy or components of which there are many installed might also be better of with the run-to-failure maintenance strategy compared to other strategies.

For critical equipment this strategy is not beneficial, but for small and cheap parts it could be. For the idlers and rollers in a conveyor belt system it could be more expensive to monitor all rollers individually instead of letting them run to failure. There are hundreds of thousands of these rollers installed and it is not a complete disaster when one of them breaks down. Operation is still possible when few rollers are missing. Of course some in between checks could be beneficial to get rid of some faulty rollers whenever the belt is not in operation. But during operation the run-to-failure strategy makes sense for these components.

Pros: No extra maintenance cost for in between checks and no extra downtime for in between checks. **Cons:** Only beneficial for smaller parts or parts with short lifetime expectancy.

Preventive maintenance

Preventive maintenance is maintenance that is scheduled at regular intervals to prevent breakdown or malfunctioning of equipment. The interval can be time based or based on operational hours or based on a certain amount of cycles (like changing on a car every 10.000 kilometers). The interval may be based on previously observed degradation of components. The time between maintenance can vary for different types of machinery and is often used for lubricated components. An example of preventive maintenance is the periodic oil change in a gearbox after a specific amount of running hours [64].

It is possible to prevent major breakdowns with preventive maintenance (hence the name). But, maintenance is performed regardless of the equipment's actual condition. This method could therefore be responsible for unnecessary repairs or replacements of a component that was fully operational, but had to be maintained because of the schedule that was made in advance. Premature maintenance is accompanied by loss of time and money, let alone the environmental footprint that unnecessary repairs and replacements create [68].

For lubricated components preventive maintenance is recommended, based on the schedule of the manufacturer. Other parts that are more expensive will benefit from regular checks, where a malfunction is hopefully caught in an early state. For the components where a run-to-failure maintenance strategy is not applicable (or not at all beneficial), a preventive maintenance strategy might be a better solution. At EMO B.V. this is the case for electromotors, gearboxes, larger components and more expensive components. But there might be an even better solution.

Pros: Regular checks will hopefully catch malfunctions in an early state, or at least before a complete breakdown of the equipment. Lubricants are replaced more often to keep the equipment healthy and prevent wear and tear. **Cons:** Maintenance is done regardless of the equipment's conditions, which could lead to unnecessary repairs and maintenance. Regular checks with no outcome can be a waste of time, effort, and money.

Condition based maintenance

Where preventive maintenance comes short and might lead to unnecessary checks and repairs, condition based maintenance actually checks the equipment's condition before acting upon it. As the name suggests, the condition of the equipment is monitored. When early signs of a malfunction occur, or when irregularities are recognized, the system might give a warning to check for malfunctions. This warning must be added to the software and is initiated when a parameter exceeds a certain threshold. This will help preventing more damage, leading to less downtime and maintenance cost.

Condition based maintenance involves not only condition monitoring tools like sensors and data acquisition, but also requires diagnostic tools for using the data and creating thresholds. This might take some time and investments, but will eventually help in reducing downtime and maintenance cost.

Pros: Maintenance is done based on the equipment's condition. Early signs of malfunction will trigger a warning before greater failure consequences occur. **Cons:** It takes some time to implement and adjust the correct triggers and thresholds. It also requires investments in software and diagnostic tools.

Predictive maintenance

Predictive maintenance is condition based. Parameters of components are measured constantly and when an irregularity occurs, maintenance will be scheduled. Predictive maintenance is a lot like preventive maintenance, but with constant monitoring of components.

Predictive maintenance is scheduled, like preventive maintenance, but it is not scheduled on beforehand for a certain of operational hours or running cycles, as is the case for preventive maintenance. The sensors collect data and based on that data the software will decide whether or not the machinery is in a good working state or that it requires maintenance. In that last case, the software must decide when the maintenance should be done. The sensors can pick up a slight irregularity and decide to keep the machinery running when it is not in an emerging state. In that case, the software will schedule the maintenance for later.

Pros: The software will decide when the best time for maintenance will be, according to previous data. **Cons:** Predictive maintenance comes with a large investment in sensors, data acquisition and software for predicting outcomes. The data must be accurate and of good quality as well. Once the implementation is done, the software must keep learning with new data and new malfunctions. This also requires a certain level of understanding from the staff. There is always a possibility that the software is incorrect. Fully relying on predictive maintenance might also lead to taking too little action when a malfunction occurs without being noticed by sensors.

2.4. Current maintenance strategies at EMO B.V.

EMO B.V.'s current maintenance strategies include a combination of run-to-failure maintenance, preventive maintenance and some tests for condition based maintenance. The run-to-failure maintenance strategy is mostly used for components which are not that critical and for components of which condition monitoring would cost more than replacing it with a run-to-failure maintenance strategy. This strategy is also used for components that come in high quantities, like idlers (of which there are over 100.000 installed and one failing would not be critical).

Condition based monitoring	**Preventive maintenance (calendar, cycles, operating hours)**	**Run-to-failure maintenance**
Rubber	Oil, greases and filters	Non-critical small components
A few idlers	Brakes	Small electromotors
Drums	3D scanners	Electric components
Grabbers	Electrical switch gear	Wheels
	Main electromotors	Idlers
	Mobile equipment	
	Gearboxes	

Table 2.3: Current maintenance strategies at EMO B.V. (2022)

As can be seen in table 2.3, some idlers do have condition based maintenance. These are a couple of idlers tested by third parties like Küpper and Rulmeca. These companies chose the terminal of EMO B.V. to test their condition monitoring techniques for idlers. One of the techniques is to measure temperature of the idlers, but this comes with expensive built-in sensors and these idlers are only to be replaced by the company itself. In addition to that, the temperature does increase on a sunny day, also leaving one side of the idlers in the sun and the other side in the shades. This took some time to implement in the system and it is still learning.

2.5. Problem statement

As discussed in the previous sections, all maintenance strategies have their advantages and disadvantages. Therefore it makes sense to use different strategies on different equipment or components. This section describes the problem statement of the current situation.

It makes sense to use different maintenance techniques on different components of the same equipment. Smaller parts that can be stored in the warehouse might be better of on a run-to-failure maintenance strategy, because preventive or condition based maintenance might be more expensive than actually replacing the part. For example, there are a couple hundred thousand idlers installed on the terminal that keep the belt supported and operating smoothly. Every meter there are three idlers to support the belt. If one idler fails, it might not be that bad for the entire operation. With regular checks as is done with preventive maintenance, these idlers can be replaced or scheduled for replacement if they do not harm the operation.

Larger and more expensive parts like electromotors cannot benefit from a run-to-failure maintenance strategy. These components must be checked continuously on early signs of failure. At the moment this is not checked continuously, but regularly with preventive maintenance. These components will benefit from condition based maintenance, where condition monitoring tools will pick up early signs of failure and trigger an alarm or give a warning to check upon these early signs of failure.

Even though condition based maintenance and condition monitoring require some investment, EMO B.V. already has a lot of condition monitoring data that can be used for a new maintenance strategy. There is room for improvement as there is lots of data available that is not yet used at its full potential.

2.6. Conclusion

"What is condition monitoring and what are different maintenance strategies? What is EMO's current maintenance strategy?"

The most common types of maintenance are: run-to-failure, preventive, condition based, and predictive maintenance. EMO B.V. uses mainly run-to-failure and preventive maintenance strategies and has some test set-ups for condition based maintenance. The current maintenance strategy can be improved by taking condition based maintenance into account. Since EMO B.V. already has a lot of condition monitoring data available, it makes sense to use this for a new improved maintenance strategy. In the next chapter this existing condition monitoring data will be discussed.

3

Condition monitoring data at EMO B.V.

This chapter will answer the sub research question *"What condition monitoring data is available at EMO, how is it obtained, and how can this be used for planning maintenance?"* The first section will explain the different condition monitoring sensors and techniques are installed at EMO B.V. or proposed to EMO B.V. The second section will explain the SCADA (Supervisory Control and Data Acquisition) interface with real-time data. The last section will conclude this chapter.

3.1. Existing condition monitoring techniques in a dry bulk terminal

The following condition monitoring techniques are installed at the terminal of EMO B.V. or have been offered to test at their terminal. Some techniques are used in other industries as well.

ABB Ability smart sensor

This small and flat sensor type can measure vibration (axial, radial, and tangential) and temperature. The magnetic field and acoustic signals are measured as well and used in calculations (data is not shown). Eventually the vibration is analyzed via a Fast Fourier Transform and a time waveform [8].

ABB Ability smart sensor for mounted bearings

This small (only 60.5 mm long) screw-on wireless sensor can measure changes in temperature and vibration signals, with a frequency range of 1 up to 1600 Hz. This sensor lasts for a year when measurements are taken once an hour and data is collected once a day. The battery is not replaceable, which means it needs to be replaced every year [7].

This sensor is a condition monitoring solution for low voltage motors. It is a flat small sensor in a stainless steel and thermoplastic case, which is attached to the cooling ribs of the motor frame. The sensor has a measurement range of minus 40 to 85 degrees Celsius with an accuracy of 0.5 degrees Celsius [9].

IFM vibration monitoring

IFM has systems for vibration monitoring according to ISO 10816 to detect damage at an early stage and to avoid consequential costs. The monitoring system is able to detect looseness or unbalance of the equipment, but also misalignment, wear and damage in bearings, gearbox meshing and tooth faults. Analysis of data is done by IFM's software program called Octavis [32] [31].

Flender Siemens DX500

Belts 111 and 134 have the Flender Siemens DX500 systems installed which measures vibrations of the gearboxes and bearings. At belt 111 both engines have these vibration sensors installed on their gearbox and bearings, measuring the effective velocity in mm/s. Belt 134 has one engine where the sensor is installed, measuring the effective velocity of one gearbox and two bearings.

ABB Ability smart sensor for mounted bearings

This small (only 60.5 mm long) screw-on wireless sensor can measure changes in temperature and vibration signals, with a temperature range between minus 30 and 85 degrees Celsius, with an accuracy of 2 degrees Celsius. This sensor lasts for a year when measurements are taken once an hour and data is collected once a day. The battery is not replaceable, which means it needs to be replaced every year [7].

Rulmeca intelligent idlers

Rulmeca measures the temperature in idlers while they are rolling, meaning while the belt is running. The sensors generate their own energy by rolling and only send out a signal when active. Whenever a sensor is down, this is not noticed, because no signal also could mean that it's not active. When having multiple sensors in the same belt installed it is easier to check whether a sensor is not sending a signal because it is failing or because the belt is not running.

The sensors measure the temperature in the idlers when they are in operation. A signal is sent to the software, which can be seen on remote. Whenever a temperature exceeds a certain value (which is to be determined depending on the environmental temperature and is compared to the temperature of the other idlers), an alarm is sent to the software and to the operator. Unfortunately the system is only sensing, not yet controlling the belt conveyor. The decision maker is a human being. This is also because when a bearing comes loose and catches fire, it is not best to stop the belt. It is actually better to keep the belt running, because then the fire stays small. When the belt is stopped, the fire has a chance to grow and then the belt will be fire, causing more damage spreading the fire. The fire must be extinguished either while the belt is running or directly when it is stopped.

Idler temperature

The idlers in conveyor belts play an important role in the functioning of the belt conveyor. If an idler is damaged, it can easily damage the belt as well. Therefore, it is important to detect a failing/ damaged/ malfunctioning idler as soon as possible and replace it before it will damage the belt [60].

Another issue is when bearings inside the idlers overheat. This could lead to very high temperatures, causing the material to catch fire.

Currently a test set-up is created by three companies: Küpper, Rulmeca, and Sensite solutions. These test set-ups are all placed to monitor the temperature of the bearings inside the idlers.

Küpper has a test set-up of their sensing idlers in 30 idlers in belt 130. Küpper implemented temperature sensors in the idlers, with the disadvantage all idlers have cables on both sides. This means six cables for every roller support beam, since there are three idlers per support beam. The Küpper solution also requires a small box with a battery and an antenna web interface per support beam. The solution compares the values of the sensors with its surroundings, making it a learning system. The advantage of the Küpper solution is that the sensors send a continuous signal to the receiver. When the temperature reaches a certain value, a warning will be sent. Unfortunately it is a high cost solution when implementing this to all the rollers in the terminal.

Figure 3.1: Schematic overview of the Küpper solution for monitoring temperature in the bearings of the idlers [73]

A test set-up of Rulmeca's intelligent idlers was installed on 12 top idlers and 8 bottom idlers in belt 100. Rulmeca has implemented temperature sensors inside the idlers with a wireless connection to the control room. The energy required for the sensors is gained by the rolling of the idlers. The advantage here is that there are no cables on the idlers themselves, but this also comes with the disadvantage that it is hard to identify from the outside which idler sends a signal. For the Rulmeca intelligent idlers, a signal is only sent when the temperature reaches a certain value. This means that if the sensors are not sending signals to the control room the temperature is below a certain value, but it could also mean that the sensor is not working. This makes the system less reliable.

In short, the advantages of the Rulmeca intelligent idlers are that they are capable of monitoring both temperature and speed, the idlers generate their own energy, and it is possible to replace idlers as usual (no extra cables). The disadvantages consist of the lack on analysis and notifications on dangerous values, it requires multiple antennas, and it requires a web interface.

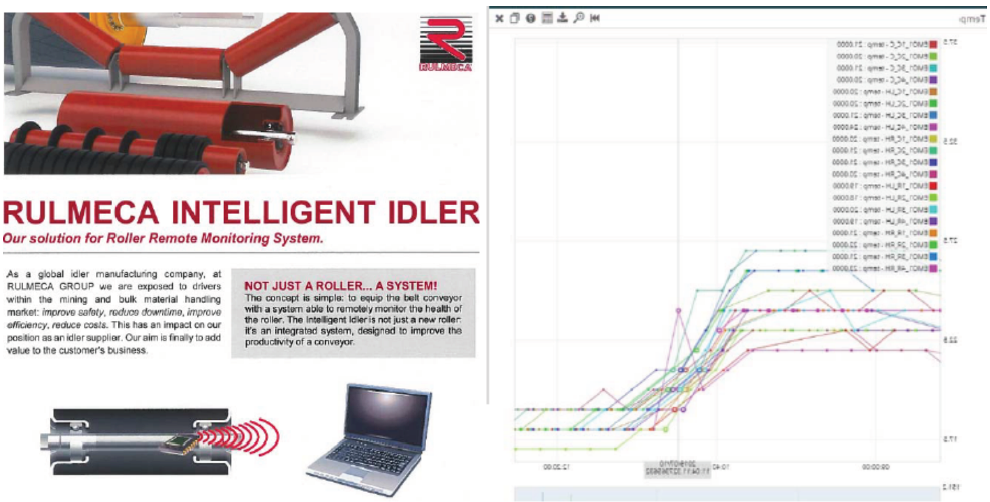


Figure 3.2: Schematic overview of the Rulmeca intelligent idler solution for monitoring temperature in the bearings of idlers [73]

Sensite solutions has temperature sensors (with cables) installed on bearing blocks, gear boxes, and weighted (bottom) idlers at belts 071 (train loader 4), 119 (train loader 3), 114 (silos), 115 (Uniper), and 214 (silos). It is a box attached to the outside of the equipment. For the reader infrastructure a network of HBL200/02 readers is used. Besides this network, a glass fiber cable operates a separate network. For both networks Master units will be placed to transmit the collected data via a TCP/IP connection to the central server. Extra Slave readers (these require 230 V) are placed in the tunnels to transmit the data to the Master units. The HBL200 readers form a wireless and self configuring redundant network.

Figure 3.3: Schematic overview of the Sensite solution for temperature monitoring in idlers, gear boxes, and bearing blocks [73]

Another solution is installed at belt 114 and is to be developed for other belts in the terminal as well. Data is gained via Wifi/ access points and the interface is in Scada. The advantage is that there is continuous monitoring and the interface is done in EMO's own system (PMB). The disadvantage is that there is no notification or analysis yet, multiple access points are required, and after replacing an idler the sensors have to be replaced as well.

Figure 3.4: Schematic overview of EMO's own roller monitoring system [73]

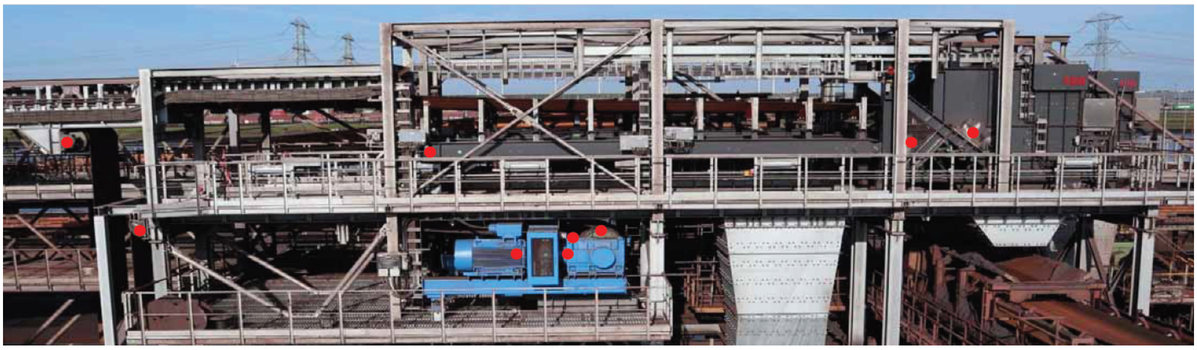


Figure 3.5: Schematic overview of EMO's own roller monitoring system [73]

TES belt tracking monitoring

TES automated belt tracking monitoring system uses inclinometers to detect belt tracking. On both sides of the belt an inclinometer measures the distance to the bulk material. Whenever these distances differ too much from each other, action is taken. The steering plate will be re-positioned (as shown in the right figure of figure 3.7) so that the bulk material will fall on the belt with a different angle, resulting in a different deviation of the bulk material on the belt, changing the position on the belt and also the amount of belt tracking. This process is ongoing and the steering plate will keep re-positioning as long as there is belt tracking detected [18].

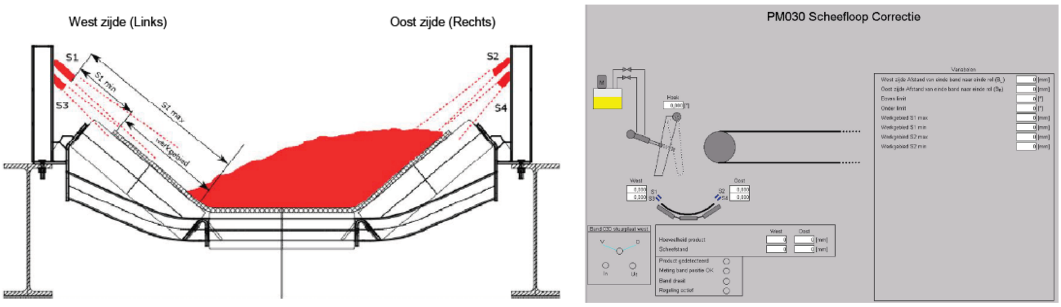


Figure 3.6: Condition monitoring and automatic correction of TES [18]

indurad iBeltAlign belt tracking monitoring

indurad's iBelt system makes use of a linear dynamic radar (iLDR) they developed. An iLDR is installed on both sides of the conveyor belt and measured the distances to both the belt as the bulk material. It is possible to connect this data to a control loop with the deflector plate adjustment mechanism in a transfer chute. This results in a condition monitoring solution where belt tracking is detected, and a decision is made to change the position or angle of the transfer chute's deflector plate, in order to fix the belt tracking.

With indurad's condition monitoring solution of iBeltALIGN, stops because of belt tracking are avoided. Damage on the belt because of belt tracking can be prevented as well, increasing the belt's lifetime, and unplanned downtime will decrease, while up-time is being increased. Fixing belt tracking might also prevent belt scratching on structural parts and avoid heat generation [37].

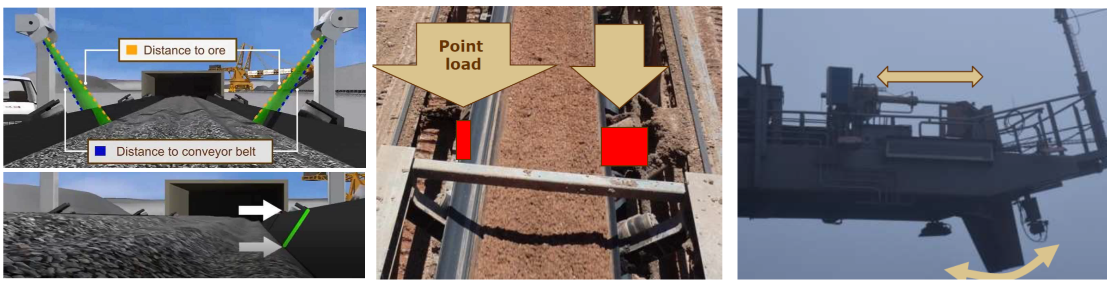


Figure 3.7: Condition monitoring and automatic correction of TES [18]

indurad iBeltWear rubber quality

Besides belt tracking, indurad has a solution for measuring the quality of the rubber by means of the thickness. A linear dynamic radar (iLDR-H 2000 Hz) and a precision linear drive (iPLD) are installed at the head idler (pulley) or below the belt (pressure idler). It takes almost two days to scan a conveyor belt system of 1450 m (meaning the rubber belt itself is 3051 m long). The belt is divided in sections of 20 mm width, which divides the belt into a hundred lines. Every line is the entire length of the belt and with a speed of 4.5 m/s (belt speed at EMO B.V.) it takes over 43 hours to run the entire belt continuously and create a full map. With a frequency of 2000 Hz the solution measures the thickness of the belt every 2.25 mm (4500 mm/s divided by 2000 /s).

This solution can locate belt damage in an early state and operators can make a maintenance planning based on the damage that was detected. The belt's lifetime is increased by repairing damage that was detected by indurad's solution, which might not have been caught without [37].

Fire in storage piles

Coal is stored in large piles in the open air at the terminal. In the deeper layers of the pile, temperature could raise due to exothermic reactions and decomposition, promoted by air and moisture. Self-ignition usually starts within the deeper layers of the pile. This could lead to a full-blown fire, without being noticed in an early state. Once the fire reaches the upper layers of the pile, smoke and flames will be noticeable, but the fire is bigger than it seems. This causes a lot of damage to the coal. These self-ignited fires can easily be detected in an early state by infrared cameras. A small investment in infrared cameras could prevent major fires by taking measurements as soon as a higher temperature within the piles is detected.

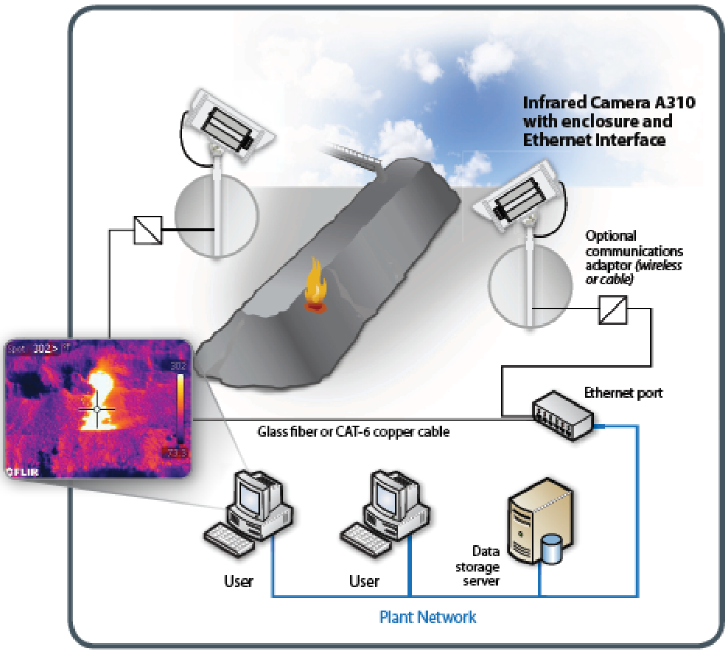


Figure 3.8: Infrared solution by FLIR [30]

Aspen Technology

This section is based on the presentations and offers that Aspen Technology Inc has proposed to EMO B.V. [28].

Aspen Technology services corporation made a proposal for optimizing asset performance. Aspen Technology proposes a virtual twin system (from the entire plant or from one machine) using a flow-based Monte Carlo simulation to identify and quantify reliability risks and the overall impact and costs associated with asset downtime. Aspen Technology claims the following benefits with their system:

- Quickly identify and quantify the downstream implications of asset downtime
- Support fact-driven choices of when to take the assets down considering all stakeholders
- Evaluate alternative downtime mitigation options to identify optimal option
- Predicts the future performance of process systems and quantifies the value of improvement opportunities

RAM model = Random Access Machine model. According to Wikipedia it is an abstract computational machine model identical to a multiple-register counter machine with the addition of indirect addressing.

Aspen Technology suggests to put a RAM model for each operating unit.

- Confirm production capacities and planning

- Confirm operational business plans and targets
- Optimize maintenance spares inventory
- Validation of projects, infrastructure changes, etcetera
- Validation of schedule or shift changes

Aspen Technology can install a RAM model for critical equipment, like the stacker reclaimers. RAM models on critical equipment will make it possible to optimize maintenance tactics and to optimize maintenance schedules (mill relining, furnace rebuilds).

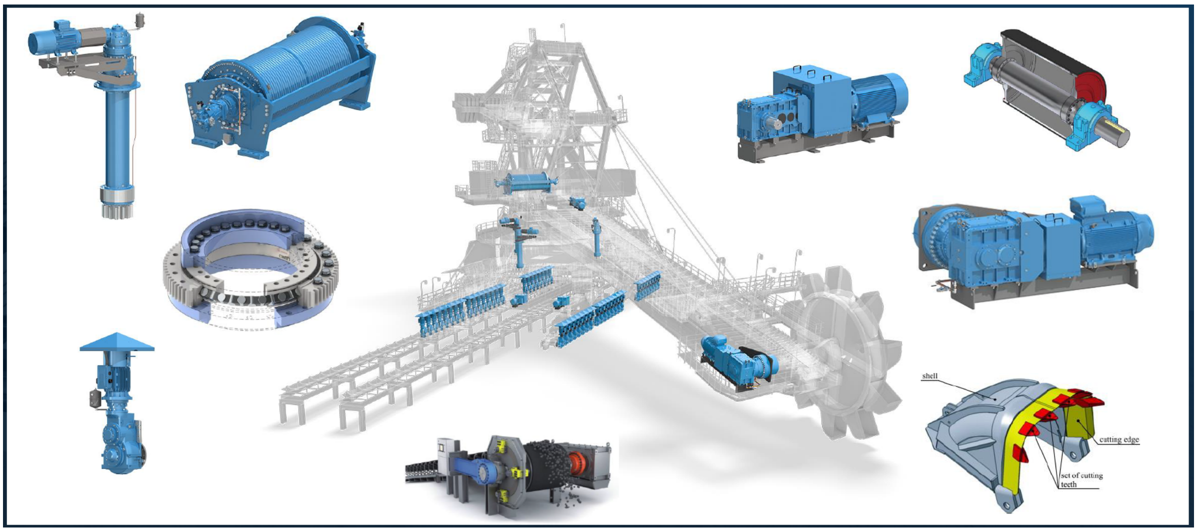


Figure 3.9: Stacker reclaimer system RAM model by Aspen Fidelis [28]

AspenTech will perform an offline Aspen Fidelis Proof of Concept project for the EMO Rotterdam Facility. The Fidelis model is intended to be built during a series of remote working sessions. The base case model will be built to cover the dry bulk material handling infrastructure for the primary products (iron ore, coking coal and low ash coal) as well as the major service areas of the Facility (transshipment, storage, washing, crushing, screening and blending).

The model(s) can then be used to identify the equipment or parts of the process that are affecting the overall performance of the Facility aka "Performance Killers". The models can also be modified, and the simulation rerun to address specific configuration changes or operating options that the customer wishes to investigate. It is intended that the number of simulation cases be limited to between 5 and 10 as mutually agreed upon during the remote working sessions. Insights provided by the simulation can be incorporated into the EMO Rotterdam production planning system to support the "Deliver to Promise" initiative.

Aspen Technology calls their project for EMO the "Road to 85% utilization" and want to ensure improved reliability, safety, and service level at the EMO terminal. Aspen Technology wants to do this through deployment of prescriptive maintenance (Aspen Mtell) to mitigate the losses focusing on identified performance killers (site license). With Aspen Fidelis a continuous model is created for future operating scenarios, managing risk so EMO is able to predict, respond, optimize, and to realize maximum business results. What is needed for all this is RAM POC from Aspen Technology. This will:

- Identify the performance killers impacting the business and prioritize
- Quantify the losses
- Identify opportunity areas to increase average facility utilization from 80% to 85%

Steps to follow:

- Identify the performance killers impacting the business
- Identify opportunity areas to increase average facility utilization from 80% to 85%
- Quantify the implications of equipment failures and asset downtime (highest number of failures versus highest losses resulting from failures)
- Mitigate the economic losses with Aspen Mtell prescriptive maintenance solution

Digital twin

A digital twin is a virtual model of a certain piece of equipment, which has a real-time connection with the actual equipment and simulates the physical state and behaviour of the equipment in real-time. A digital twin is an effective replica of its physical asset and makes easy visualisation possible, as well as smart decision making and cognitive capability in the system [75].

The first step to creating and developing a digital twin is to collect data. This could be historical data or real time data that will be stored. The next step is to prepare and fix the data where necessary. Fixing data is required when data is missing or when irregularities (like signal noise) are involved. This step often includes filtering, removing noise, and other methods to process the raw data.

The third step is to use different machine learning models to build a digital twin and implement the collected and processed data. The following step is to deploy the model. This step is taken when the digital twin is working properly and when it is able to read data and return results. Finally, the model must be maintained and continuously be developed and refined by collecting new or more data. These steps can be summarized as: monitoring, visualization, storage, analysis, and control.

For developing a digital twin, consider the following questions [75]:

- What variables in the physical domain can be extracted?
- How should the number and deployment of sensors either during design time or during the usage time (for legacy systems) be selected?
- How can a digital twin model be developed given the constraints of resources (i.e. sensors and costs)?
- When should the digital twins (as lightweight as possible to meet the resource constraints) be updated to make sure that they can accurately predict system performance?

At conveyor belt system 111-134-135 several vibration sensors and temperature sensors are installed. With Radmin it is possible to check the real-time values of the sensors at station B.

The frequency converters are placed on belts 111, 121, 130, 161, and 240.

Symbol	Meaning	111	121	130	161	240
V_{ref}	Reference speed [100%]	1	-	-	1	1
V_{bnd}	Belt speed [%]	1	1	1	1	1
N_x	Rotational speed [RPM]	2	2	2	2	4
Trq_x	Torque [Nm]	2	2	-	-	-
P_x	Power [%]	2	2	2	2	4
$dNdt_x$	Acceleration [RPM/min]	2	2	-	-	-
T_{FUx}	FC temperature [°C]	2	2	2	2	4
T_{Mx}	Motor temperature [°C]	2	2	-	-	-
I_x	Current [A]	-	2	2	2	4

Table 3.1

3.2. SCADA

SCADA stands for Supervisory Control and Data Acquisition and a schematic overview is given in figure 3.10 [26]. At EMO B.V. there are multiple remote stations located at the terminal. Every station is responsible for a couple of belts in the neighborhood with their sensors and measurements. The parameters are measured by sensors as described above and are presented in real-time. The data is updated with 10 Hz, meaning 10 times per second. This accompanies the need for a large data warehouse.

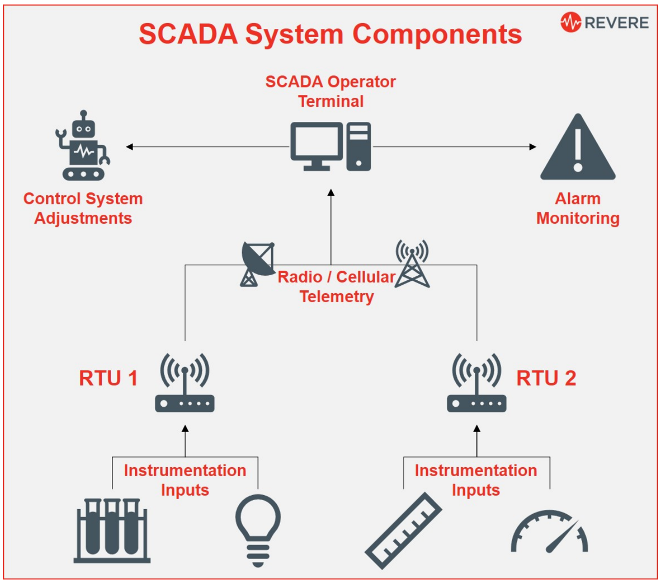


Figure 3.10: Schematic overview of SCADA (Supervisory Control and Data Acquisition); RTU means Remote Terminal Unit [26]

The stations located on the terminal are the RTUs (Remote Terminal Units) in this overview. An RTU converts the signal from the components to data. This data stream - this is called telemetry in this schematic overview - is sent to a central location, before sending it to the operator terminal. With automated data loggers there is less need for constant supervision and operators per station. At EMO B.V. the stations are not manually operated, all data is sent and stored automatically.

There are 10 stations spread over the terminal of EMO B.V. and each station has its own server and data logs. Some of the belts are logged in two different stations, this is because some belts are longer and pass by multiple stations or have drive units installed at different stations. Station A, D, G, H and Y have the old WinCC application, which makes it not possible to extract actual data in excel. The other stations do have the possibility to extract data, but only save data for one or two weeks. In table 3.2 the different stations are shown with their condition monitored conveyor belts.

Station	Conveyor belts
A	010 020 030 100 110 120 210 220
B	111 121 130 161 240
D	144 145 154 250 340
F	161 221 230 240
G	010 020 030
H	146 154 215 260
K	070 071 116 117 118 119 ROB1-6
M	014 040 171
V	270
Y	080 151 164 165 171 181 182 250 270

Table 3.2: Stations at EMO B.V. with their condition monitored conveyor belts

Almost all belts are logged with their input data and actual measured data. This data is not stored forever, but logged for several days or weeks, depending on the belt or station. The data that is logged depends on the belt. Most belts have their power logged in percentages, torque in percentages, belt speed in percentages, and current in Ampères. Some more important belts like the ones underneath the bridges (010, 020, 030, and 040) have more data logged. For these belts the rotational velocity N (rpm), acceleration dNdt, actual tension on the winch p_{Spl} (bar), desired dynamical set point of the winch, rotational velocity N (rpm) of the winch, and sometimes the droop is logged as well. The temperatures of the frequency transmitters and engines is measured as well (in degrees Celsius) and logged. In the following figures the different data logs are shown.

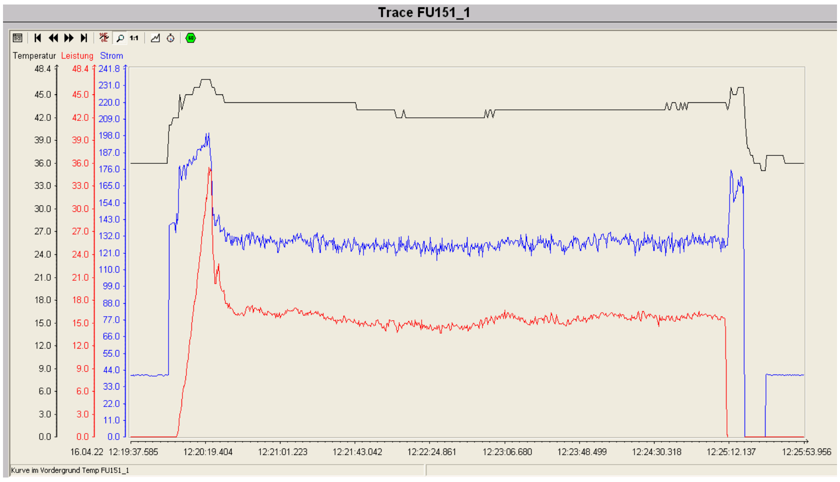


Figure 3.11: Condition monitoring data in SCADA at station Y for conveyor belt 151, screenshot taken at 16 April 2022

Figure 3.11 shows the parameters for conveyor belt 151, measured at station Y. This picture shows the temperature of the frequency controlled drive unit (black) and its power (red) and current (blue). This figure shows a normal start up and stop of the belt.

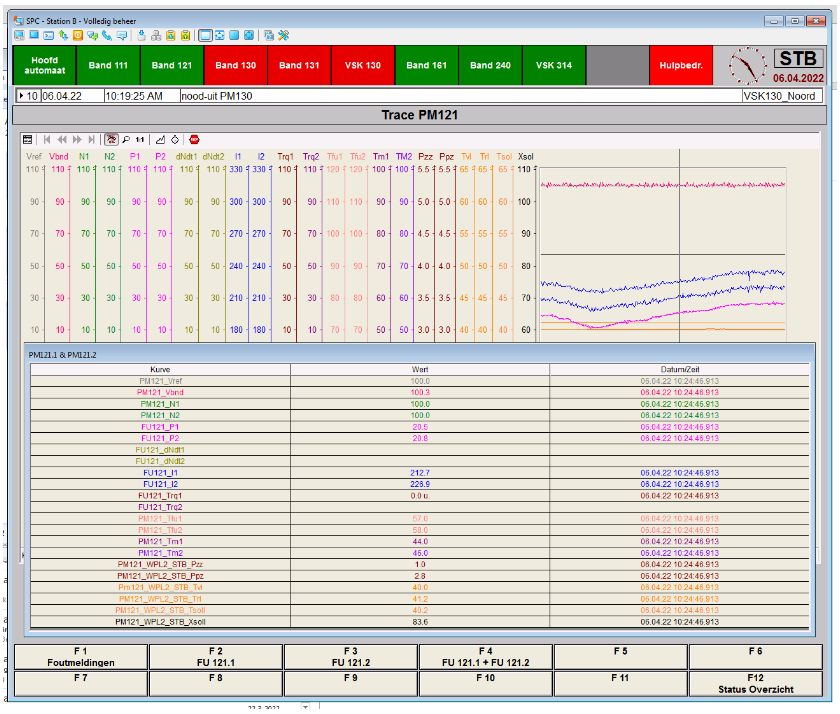


Figure 3.12: Condition monitoring data in SCADA at station B for conveyor belt 121, screenshot taken at 6 April 2022

Figure 3.12 shows a screenshot of the condition monitoring parameters of conveyor belt 121. At this picture there is a lot more parameters shown than on the previous one, figure 3.11. This shows that different stations and different conveyor belts have different sensors. In this picture the speed of the belt, torque, power, cycles, current and more is shown for the two drive units of conveyor belt 121.

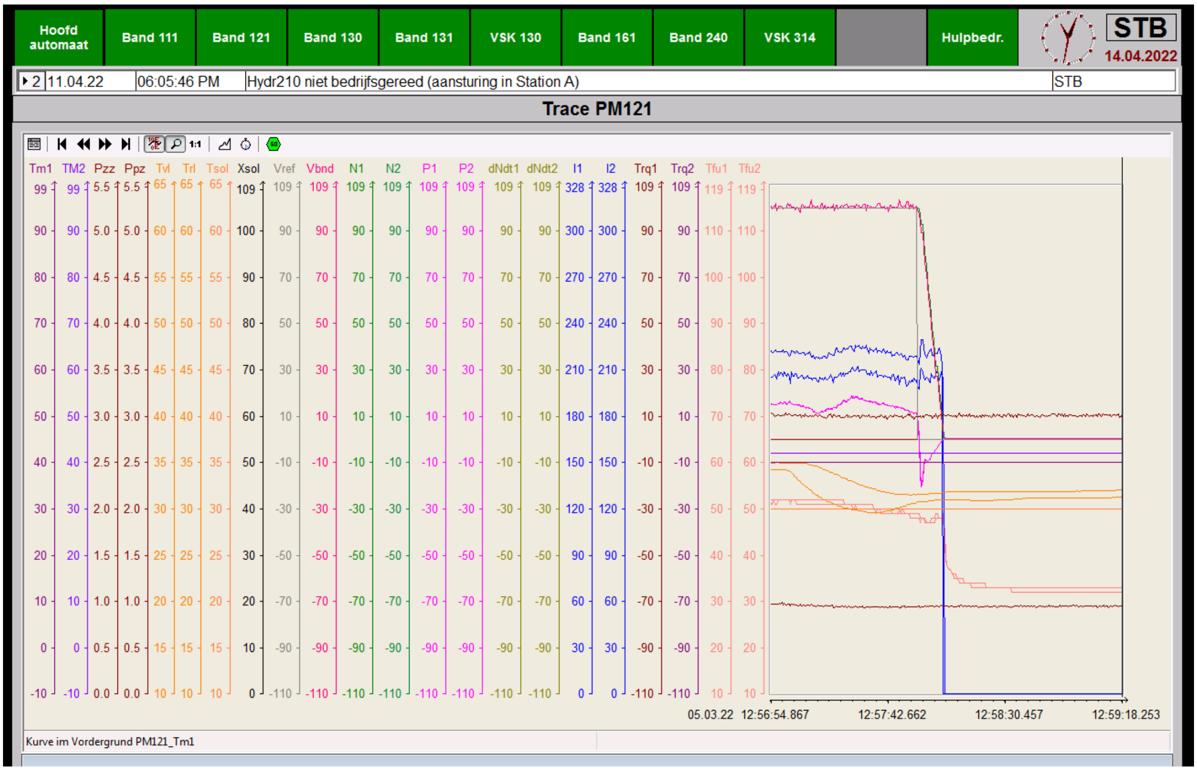


Figure 3.13: Condition monitoring data in SCADA at station B for conveyor belt 121, screenshot taken at 14 April 2022

Figure 3.13 shows an emergency break of conveyor belt 121. As can be seen, all parameters have a sudden stop. Normally, when the conveyor belt is stopped, the parameters have a more gradual stop, like in figure 3.11.

These figures are shown to create a visible interpretation of the data at EMO B.V. and will not be discussed into detail in this chapter. When applying the new maintenance strategy to real life events, their traces/ data will be discussed.

3.3. Conclusion

"What condition monitoring data is available at EMO B.V. how is it obtained, and how can this be used for planning maintenance?" There is a lot of data available at EMO B.V. and most of it is found on the conveyor belt systems. Some solutions are already in use, however some seem to be unnecessary. The most important data is gained from the SCADA software where all the input variables and output parameters are measured at 10 Hz and stored in a large data warehouse for an average time of two weeks. This data will be used for the new maintenance strategy whenever a malfunction with large failure consequences will occur at the terminal.

4

New maintenance strategy

This chapter will answer the sub research question *"Which methodology is best to create a new maintenance strategy?"* The first section will set up the criteria for the new maintenance strategy. The second section will discuss the different maintenance strategies and risk assessment methodologies and address whether these strategies suit the criteria from the first section. The last section will conclude this chapter and decide which methodology is used to create a new maintenance strategy.

4.1. Criteria for a new maintenance strategy

In order to create a new maintenance strategy, some criteria must be set. EMO B.V. has a variety of condition monitoring data from several sensors. The main idea of this thesis is to use the available data, so this will be the first criteria. For liability reasons, the new strategy must have some worldwide applicable rules and guidelines. If the new strategy is listed in the ISO standards, its guidelines will be set and applicable worldwide.

The new strategy must be able to include all the possible malfunctions and failures that the terminal experiences. Multiple causes and consequences of every malfunction must be able to be listed and adjusted if necessary. Therefore the new strategy must be adaptable and flexible.

A criticality analysis or risk assessment must be possible to prioritize the different malfunctions. Eventually the new maintenance strategy must reduce downtime and maintenance cost, while improving reliability and operation as is stated in the original assignment.

To make the new maintenance strategy highly applicable to other equipment and terminals as well, it must be applicable and accepted worldwide. One way to make this possible is by creating a new strategy based on a worldwide accepted ISO standard. This makes it easier to adapt the maintenance strategy to other terminals, other countries and other industries as well.

- Based on existing condition monitoring data
- Existing malfunctions + ability to add new malfunctions
- Causes analysis
- Consequences analysis
- Risk or criticality assessment
- Reducing downtime
- Reducing maintenance cost

- Improving reliability and operation
- Applicability and acceptance
- Main focus

Different risk assessment methods and maintenance methods are looked into to gain insight in all the possibilities for a new maintenance strategy. In the following section a selection of different risk assessment methodologies is given with a brief explanation.

4.2. Different risk assessment methodologies

Risk assessment methodologies are necessary to create a suitable maintenance strategy. There are qualitative, quantitative and hybrid risk assessment techniques. Qualitative techniques are subjective methods where risk is categorized based on likelihood and potential impact. Quantitative techniques are based on a numerical analysis to quantify risks. Examples are a fault-tree analysis, event-tree analysis and a probability risk assessment. These methods are often used in high risk industries like chemical, nuclear and aviation industries. Hybrid techniques combine the previous mentioned techniques [66] [59].

The following risk assessment methodologies will be looked into:

- FTA: Fault Tree Analysis
- ETA: Event Tree Analysis
- PRA: Probabilistic Risk Assessment
- SWOT: Strengths, Weaknesses, Opportunities and Threats
- PHA: Preliminary Hazard Analysis
- HAZOP: HAZard and OPerability analysis
- FMEA: Failure Modes and Effects Analysis
- FMECA: Failure Modes, Effects and Criticality Analysis

Fault tree analysis (FTA)

Fault Tree Analysis (FTA) is a systematic and graphical method used to analyze and assess the potential causes of system failures. It is commonly performed to identify the root causes of failures and evaluate the likelihood of specific events occurring. Events are combined by Boolean logic with the top event being the failure and the probability of this event is analyzed [59] [2].

Event tree analysis (ETA)

Event Tree Analysis (ETA) is a systematic method used to analyze and evaluate the potential outcomes or consequences of specific initiating events. The analysis starts with an initial event or action, after which following events are analyzed. This leads to the exploration of possible outcomes and helps in assessing risks, anticipating on potential consequences, and developing effective strategies for risk mitigation and response. It can be helpful alongside other risk assessment methods [59] [25].

Probabilistic risk assessment (PRA)

Probabilistic Risk Assessment provides a systematic and quantitative framework for evaluating risks, identifying vulnerabilities, and improving the safety and performance of critical systems and processes. It enables organizations to better understand and manage risks in complex and dynamic environments. First, the hazards and initiating events are identified, after which an ETA or FTA can be created. The next step is to assign probabilities and to quantify consequences. Eventually this method is used to inform risk management decisions [59].

Hazards and operability analysis (HAZOP)

HAZOP is used to identify potential hazards and is used most often in chemical industries, pharmaceutical industries and oil and gas industries. This method assesses the risks that are associated with new or existing facilities or equipment. HAZOP is often performed in teams consisting of (maintenance) engineers, operators and safety professionals. The system is analyzed and different systems or components will be identified with their respective parameters. As this is a qualitative method, words will be assigned to these parameters in order to identify the hazards. After identifying the hazards and deviations, consequences and risks are assessed and recommendations will be developed on their behalf [59].

Failure modes and effects analysis (FMEA)

FMEA is short for Failure Mode and Effects Analysis. It is a systematic method used to identify all possible failure modes of a system, a process, or a product. After identifying all failure modes, the effects and causes are identified. After investigation of the failure modes and its causes and effects, actions will be determined. The analysis will create a long list of malfunctions with their corresponding causes, effects and determined actions [71] [39].

Failure modes, effects, and criticality analysis (FMECA)

FMECA is short for Failure Mode Effects and Criticality Analysis. The main goal of FMECA is to assess the impact of those failure modes on the overall system, process, or product. Effects and causes are identified for every malfunction or failure, just as with the FMEA method. The difference between the FMEA and the FMECA method is the criticality analysis, which is based on the malfunction's severity, occurrence and detectability. The criticality analysis is used to prioritize the different failure modes. With the FMECA method it is possible to identify, analyse, evaluate, prioritize and reduce risks [24] [71] [39].

Criteria	FTA	ETA	PRA	HAZOP	FMEA	FMECA
Existing data	v	v	v	-	v	v
Causes	v	-	v	-	v	v
Effects	-	v	v	v	v	v
Criticality	-	-	v	v	-	v
Downtime -	v	v	v	-	v	v
Cost -	v	v	v	-	v	v
Reliability +	v	v	v	-	v	v
Applicability	v	-	-	v	v	v
Main focus	Cause	Effect	Risk	Safety	Failure	Failure

Table 4.1: Criteria per methodology

Table 4.1 shows that FMECA is the best suitable option for creating a new maintenance strategy for conveyor belt systems in a dry bulk terminal. While other methodologies might score high as well, FMECA's main focus is on failure and maintenance, where other methodologies focus on safety and risk. FMECA is the most complete method taking both effects and causes into account, while being applicable worldwide by an ISO standard (60812). It can also use other methodologies like FTA and ETA to gain a better overview of all effects and causes. Therefore, the FMECA methodology will be the one that is used for creating a new maintenance strategy.

4.3. Conclusion

"Which methodology is best to create a new maintenance strategy?" As can be seen in table 4.1, the FMECA methodology suits best to create a new maintenance strategy. This technique is the only one scoring positive on all the criteria. Other techniques are close, but might focus on a different aspect. For example, the HAZOP method focuses more on human safety than on maintenance of the equipment. While human safety is important, this thesis focuses on the maintenance of the equipment. Therefore the FMECA methodology suits best.

5

Implementing the new maintenance strategy

This chapter will answer the sub research question *"How is this methodology implemented to create a new maintenance strategy and how is the maintenance strategy kept up to date?"* The first section will introduce the FMECA methodology which was chosen to be the best suitable method to create a new maintenance strategy. The following sections will discuss the different steps in the FMECA method, where each section represents a step in the methodology. The last section will conclude this chapter and shows a flowchart of the proposed maintenance strategy.

5.1. Introduction to FMECA

FMECA is short for Failure Mode Effects and Criticality Analysis. It is a systematic method used to identify and prioritize failure modes of a system, a process, or a product. The main goal of FMECA is to assess the impact of those failure modes on the overall system, process, or product. The criticality analysis is used to prioritize the failure modes. With the FMECA method it is possible to identify, analyse, evaluate and reduce risks [24] [71] [39].

Failure modes are all the possible ways in which failures could occur. Each potential failure mode must be documented and described. All these failure modes have their own possible consequences or effects on the overall system. Not all of those effects are equally as bad, some are more critical. By evaluating the severity, occurrence and detectability of all the failure modes, a criticality analysis can be made to help quantifying the risks levels and prioritizing the failure modes. This means that the failure modes will be ranked by their potential impact on the overall system.

As can be seen in the overview in figure 5.1, there are certain steps to be followed to perform the FMECA methodology according to standard IEC60812 [39]. The steps shown in this overview are general steps to follow and can be tailored or customized to specific systems. The following sections will explain the steps of the FMECA methodology and how they were performed for the conveyor belt systems in this thesis.

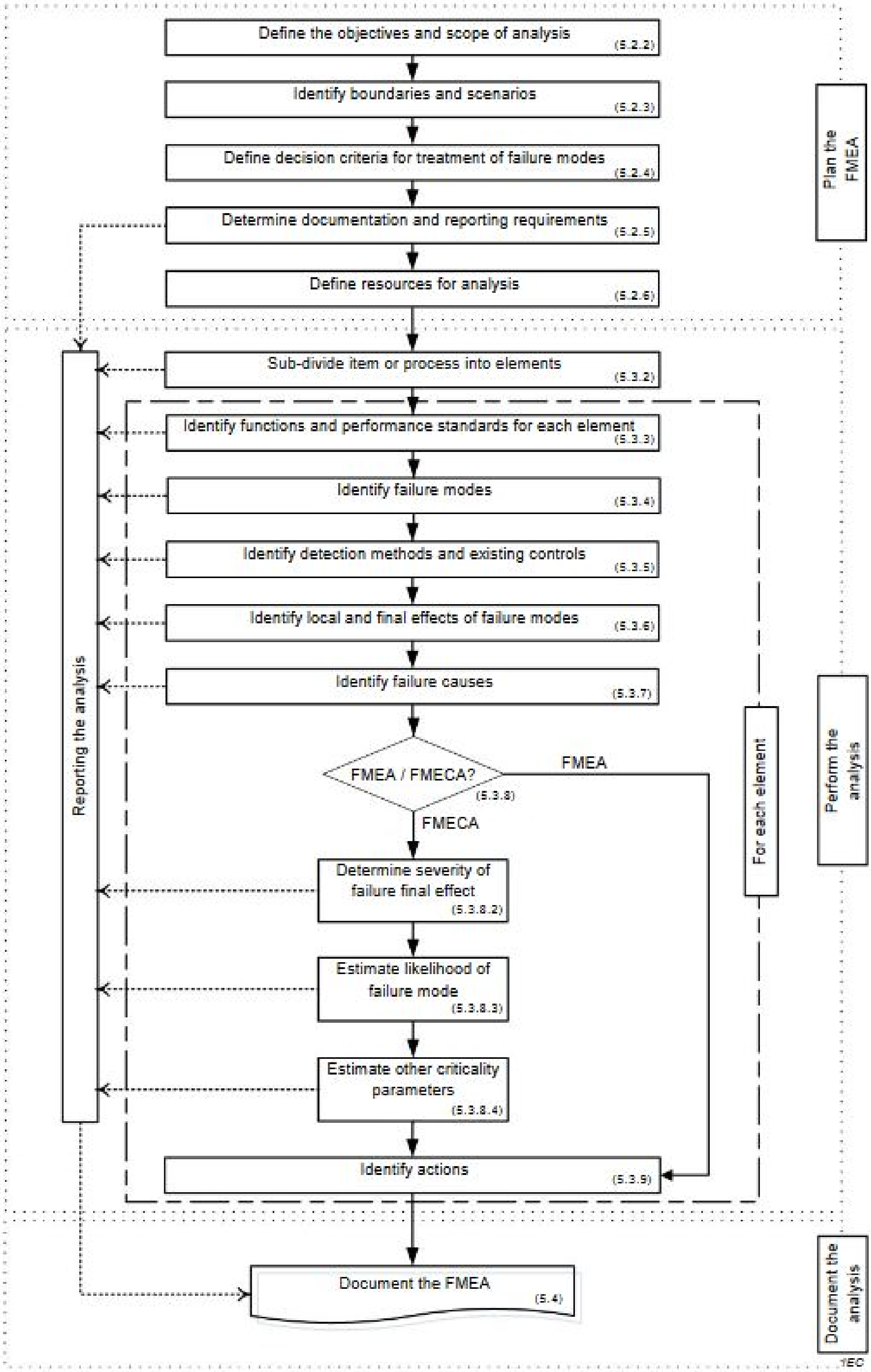


Figure 5.1: Overview of FMEA methodology before tailoring according to standard IEC60812 [39]

This general overview of standard IEC60812 [39] is altered to fit the current documentation of EMO B.V., without changing the terminal's way of handling failure modes. This means that the first block in this diagram "Plan the FMECA" is mostly defined by EMO B.V. already. This thesis will choose the (sub)system that is being analyzed and then continues to perform the analysis. This results in the following steps:

- Step 1: Define system, define boundaries (section 5.2)
- Step 2: Identify failure modes (section 5.3)
- Step 3: Identify effects (section 5.4)
- Step 4: Identify causes (section 5.5)
- Step 5: Determine risk priority numbers (section 5.6)
- Step 6: Identify actions (section 5.7)

5.2. Step 1: Define system, define boundaries

At a dry bulk terminal there is a lot of different equipment in operation as is already discussed in chapter 1. The main system that is connecting all of this equipment is the conveyor belt system. This section will explain why this system was chosen for this thesis to be analyzed. This was done in the orientation phase in the beginning of this thesis.

Malfunctions according to PowerBI and EAM

EMO B.V. logs a lot of data from the control panels in different data warehouses. One of these data warehouses is made in PowerBI from Microsoft. In this data visualisation tool all stops and warnings of equipment is logged. These are not only stops, but also warnings for belt tracking, temperature raises and more. Whenever a conveyor belt or a crane stops, for whatever reason, this is automatically logged in PowerBI. Every time a piece of equipment is started again, this is also logged. With this data it is possible to find all operational hours of every piece of equipment. In the next subsection is shown how this data is used to calculate the overall equipment effectiveness.

The majority of these stops are not actual malfunctions but operational stops. Reasons for operational stops are whenever a belt is empty, change of program, equipment is moving, etc. Whenever a stop is an actual malfunction this will be processed further in another data warehouse, called EAM (Enterprise Asset Management), where for every malfunction a work order will be created. All updates on this malfunction will be added to the same work order. Every inspection, repair, maintenance, spare parts are all manually added. Even pricing of new parts are filed in the same work order. This makes it easier for a coworker to pick up where the previous coworker ended its inspection or maintenance. Everyone is able to see the work orders and can read into it.

Overall Equipment Effectiveness

The terminal of EMO B.V. logs the operating hours from all equipment. In this data log is stored the exact time when a machine was operating, malfunctioning, broke down, or was off duty. This data is combined to determine the Overall Equipment Effectiveness, abbreviated to OEE. This is an indicator used to show how well equipment has performed according to their planned operation time. In figure 5.2 is shown where the OEE comes from.

Level 0 represents the time in general, a year for example. Level 1 divides that time into times where the terminal is open for business and when it's closed. Level 2 takes the time where the terminal is open and divides this into work and no work. Level 3 divides the working time in actual operating time and downtime. The downtime is then divided in level 4 into technical downtime and operational downtime, which is divided in level 5 into internal and external operational downtime. The technical downtime from level 4 is directly translated to unplanned downtime in level 5. Level 5 also shows a block called planned technical downtime, which is scheduled in the ”no work” time. Speed losses are part of the operating time in level 5 and level 6 shows quality losses as well. In this thesis, speed losses and quality losses are not taken into account.

Calculating the OEE will be as follows: The net operation time will be divided by the planned operation time to get the overall equipment effectiveness. OEE equals availability (operating time divided by planned operating time) times performance (net operating time divided by operating time) times quality. Quality is a non-applied factor at EMO B.V., which leaves the equation of OEE to availability times performance.

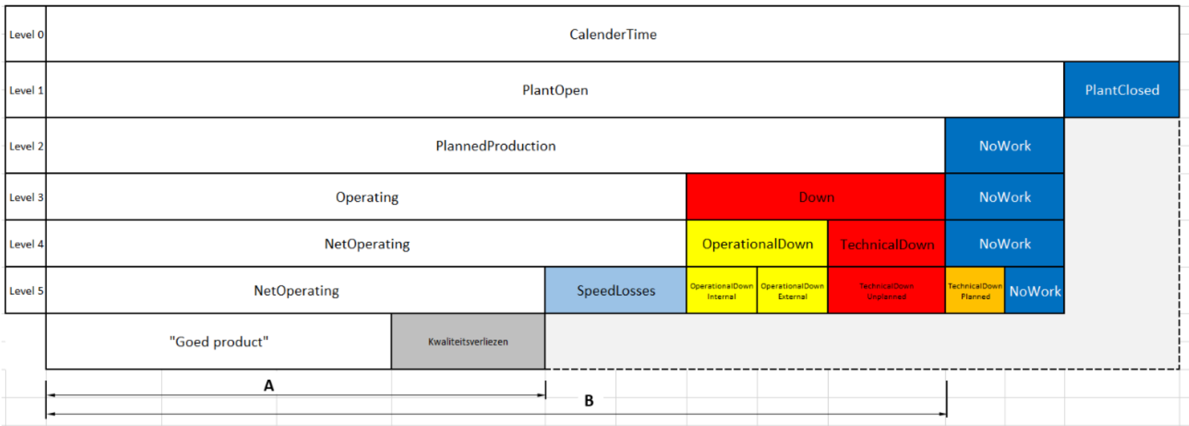


Figure 5.2: Overall Equipment Effectiveness calculation (Intranet)

Speed losses are divided into operational and technical speed losses. Operational speed losses can be caused by a change of crews, a student operator, lack of rolling material, bad load, or if two cranes are unloading on one conveyor belt. Technical speed losses are caused by technical issues, such as wear, or the condition of the equipment.

Internal operational downtime is time where the equipment is not operating because of internal or necessary actions. This could be a change of grabbers, a change of crew (when a new shift is starting), a change of program (going from coal to iron ore or vice versa), cleaning belts when the type of bulk material is changed (no mixing), or when equipment is moving (stacker-reclaimers, cranes, or barge loaders). Lack of personnel and vessel damage are also assigned to internal operational downtime. **External operational downtime** is the time where the equipment is not operating due to external influences. This could be bad weather conditions, problems with the vessel (position to quay, being late), inspections, etc. In practice, Operational downtime is not divided into these two categories at EMO B.V. For example; mist and bad weather is registered as internal operational downtime (instead of external).

Planned technical downtime is when a piece of equipment is intentionally shut down for maintenance or cleaning. **Unplanned technical downtime** is whenever a piece of equipment is malfunctioning, unable to operate, or whenever there is an inspection. It could also be that because of a malfunction the equipment needs to be repaired, replaced, or cleaned. This all contributes to unplanned technical downtime.

From the OEE percentages alone it is hard to conclude which piece of equipment will be picked as the main topic for this thesis. Most OEE percentages are between 65% and 70%. But, from the data that was used to calculate the OEE percentages (the logged data of PowerBI) some conclusions can be derived. When the unplanned technical downtime data was gathered and only the time of stops were counted, this resulted in a total downtime of 1886.34 hours over the year 2021. From this total the conveyor belts were accountable for more than 30%, 590.30 hours.

Other factors

The way that the terminal of EMO B.V. is built up, makes it possible to reroute the bulk material in case of a shutdown of equipment. Some routes are not interchangeable or have no back-up. With the map shown in figure 5.3 the back-up and rerouting possibilities will be explained.

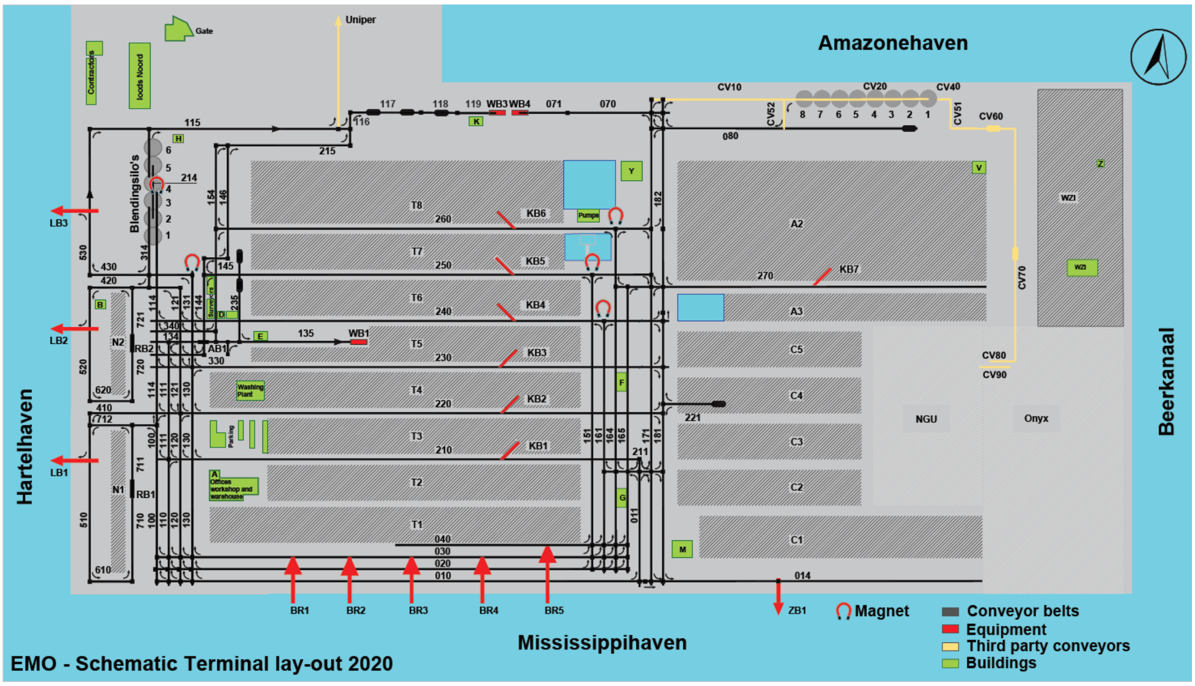


Figure 5.3: Schematic lay-out of the EMO terminal 2020 (Intranet)

The conveyor belts underneath the quay cranes are the main carriers for incoming bulk material. Cranes 1 to 4 can load bulk material on three different conveyor belts, called 010, 020 and 030. Crane number 5 has the possibility to load bulk material onto another conveyor belt, called 040. This belt is shorter than the other three and makes it not possible for the other cranes to use it at this moment. This belt might be elongated later to have more loading opportunities for the other cranes as well.

These four conveyor belts can run in both East- and West-direction. In West-direction the belts connect to the four belts in North direction; belt 011, 151, 161, 164 and 165, which have their own connection to one stacker-reclaimer line (240, 250, 260, or 270) and to train loader 4. In East-direction belts 010, 020 and 030 connect to belt 100, 110, 120 and 130, which also have their own connection to other equipment: This includes the stacker-reclaimer lines (210, 220, or 230), the barge loaders, train loaders 1 and 3 and the silos. Belt 040 does not connect to any belt in East-direction, since it is too short to reach the connector points.

Conveyor belt system and its boundaries

The orientation phase of this thesis has decided that the conveyor belt systems will be the topic of this thesis. This is based on the PowerBI- and OEE- data that was handed over in the orientation phase, the failures that happened on the terminal during that same orientation phase, the available data of already installed sensors, and the on-site running trials from third parties. The current maintenance situation and the possibility for improvement were also taken into account. Based on the literature studies as well as the experience from the orientation phase, the conveyor belt system seemed to be the most promising for the FMECA methodology.

Figure 5.4 will show all components that are part of the conveyor belt system as well as their functions. This system block diagram will give a better insight in the operation of a conveyor belt system.

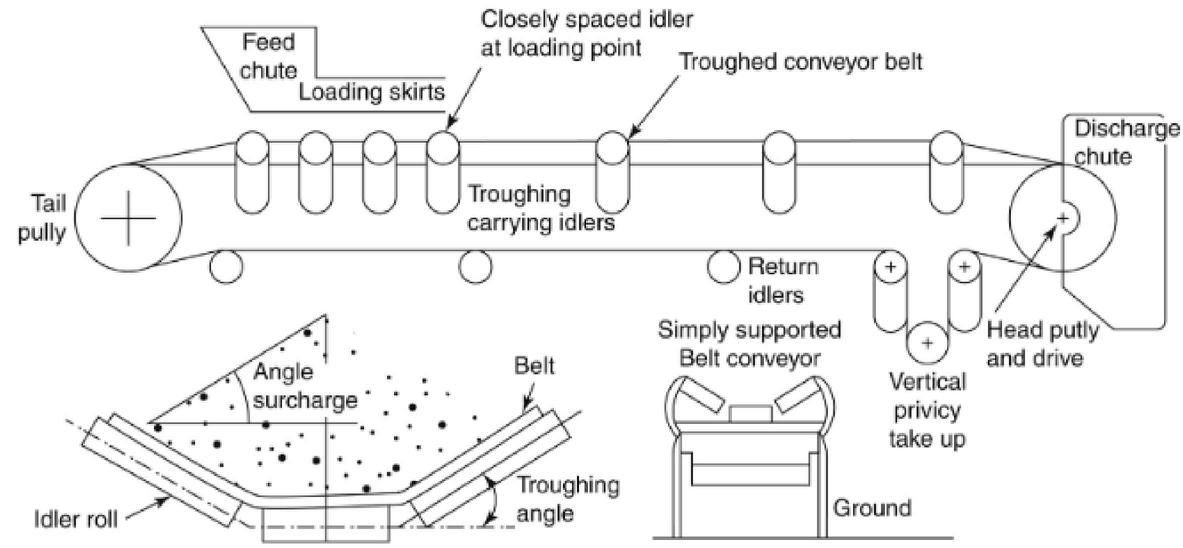


Figure 5.4: A schematic overview of a conveyor belt system [19]

Conveyor belt systems

This section will describe the components of the conveyor belt system, as previously described in chapter 1, with their function. A more detailed description of the conveyor belt system and its components can be found in chapter 1. This section will briefly discuss the functions of these components.

The **conveyor belt** itself is made of rubber and reinforced with steel cords. The terminal of EMO B.V. has over 75 conveyor belts with a total length of more than 27 kilometers. The individual belt lengths vary from 30 meters to a little over 3 kilometers. Its function is to carry and transport the bulk material that is loaded on the belt from one point to another at a constant speed of 4.5 m/s.

The **idlers** (or rollers) are supporting the conveyor belt from underneath. The carrying idlers are placed in a trough model where three idlers are placed under a troughing angle, as can be seen in the bottom left of figure 1.17. The carrying idlers are smooth and made of steel. Other types of idlers can be found at locations where more support is required and at the return belt. These are sometimes covered in rubber rings. The main function of the carrying idlers is to support the belt and the bulk material. The return idlers' function is to prevent sagging or collapsing of the belt. Other idlers are made to absorb the load from falling bulk material at deposit locations.

The **pulleys** are cylindrical drums made of steel and often covered with a rubber layer. The pulleys are placed at the ends of the conveyor belt, where the belt wraps around the pulleys. The pulleys' function is to provide support for the conveyor belt and to guide the belt at locations where the belt changes direction or tilts.

The conveyor belts are driven by a **drive unit**, which consists of an electromotor, gearbox and braking system. EMO B.V. uses a frequency controlled drive to power the conveyor belt system. The drive's function is to deliver enough torque to keep the conveyor belt running.

For changes in belt length because of changing load, temperature, or other circumstances, a **tensioning device** will take care of the tension in the belt. As discussed in chapter 1, there are different types of tensioners, but all have the same function: maintaining proper tension in the conveyor belt.

The **support structure/ frame** of the conveyor belt system is there to hold the entire system in place. It is made out of steel and provides support to the system.

Belt scrapers are located at the ends of a conveyor belt, to scrape off any remaining bulk material of the conveyor belt. This is necessary because carryback material could contaminate parts of the conveyor belt system, like idlers and pulleys. It is also important to start every operation with a clean belt, so a new product will not be contaminated with residue of the previous carried material.

Component	Function
Idlers	Supporting the conveyor belt, prevent sagging, guiding the conveyor belt
Conveyor belt	Carrying the bulk material from one point to another
Electromotor	Deliver torque to drive the conveyor belt
Gearbox	
Pulleys	Supporting the conveyor belt when it changes direction
Tensioning device	Maintaining proper tension in the belt
Structure/ frame	Support the entire conveyor belt system

Table 5.1: Functions of different components of the conveyor belt system

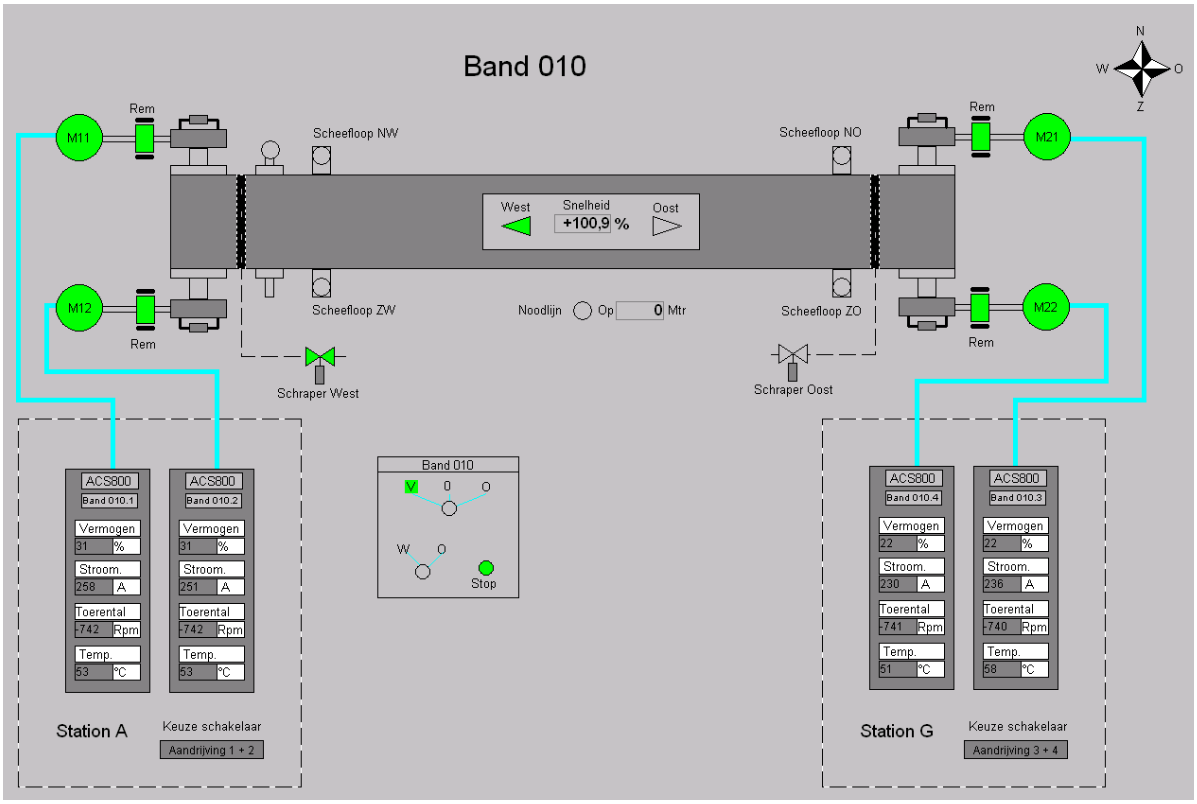


Figure 5.5: Schematic overview of a conveyor belt system [15]

Figure 5.5 shows a schematic overview of conveyor belt system 010. This is the view of a conveyor belt system in general as how it is used at the terminal. The top figure is actually the figure that is used for the operation and functioning of the steering plates on the beginning and end of the belt, but it also shows a very schematic layout of this belt conveyor. In the bottom figure the conveyor belt is shows from a top view with the current variables. Belt speed is shown in percentages, where 100% is equal to 4.5 m/s.

5.3. Step 2: Failure modes

This section will explain the different failure modes of the components discussed in the previous section and how these failure modes were assembled.

The failure modes of all components are listed in table 5.2. These failure modes were gained of the PowerBI database of EMO B.V. where all the stops of the system are logged [17]. These stops are assigned to the malfunctions causing the stops, from now on referred to as failure modes.

The failure modes need to be identified and assigned to the different components of the conveyor belt systems. The failure modes are described in the following tables. Note that it is possible that there are more failure modes than indicated. These failure modes are based on the database of EMO B.V. of actual failures. Extra failure modes are added based on papers if not existing already in the database of EMO B.V.

Component	**Failure mode**	**Component**	**Failure mode**
Idlers	Bearing failure	**Gearboxes**	Oil leak
	Overheating bearing		Gear wear
	Damaged bearing		Breakage of gear tooth
	Misalignment in rollers		Overheating
	Damaged idlers/ rollers		Misalignment
	Blocked rollers		Vibration
			Housing damage
Conveyor belt	Wear		Gear tooth damage
	Belt tracking		Backlash change
	Damaged rubber belt		
	Tear in rubber	**Pulleys**	Bearing failure
	Splice issues		Misalignment
	Steel cords damage		Wear
	Steel cords breakage		Material buildup
	Slipping belt		Slipping belt
	Emergency line pulled		Blocked pulley
	Melted rubber		
	Tensioning problems	**Tensioning device**	Bearing failure
			Misalignment
Electromotors	Failing to start		Over tensioning
	Misalignment of shaft		Under tensioning
	Bearing failure		Failing to start
	Overheating		Counterweight failure
	Winding insulation failure		Wear
	Rotor/ stator failure		Hydraulic/ pneumatic issues
	Vibration		
	Contamination	**Structure/ frame**	Cracks
	Oil leak		Tear
			Breakage

Table 5.2: Several failure modes per component

5.4. Step 3: Identify effects

The consequences of the failure modes are listed in the following tables 5.3 and 5.4. These consequences - or effects - are based on the data of EMO B.V. [16].

Failure mode	Effect
Idlers	
Bearing failure	Increased friction, heat generation/ overheating, breakage
Overheating bearing	Idler damage, belt damage, structure damage, possible fire
Damaged bearing	Bearing failure
Misalignment in rollers	Uneven wear on rollers, increasing belt wear, belt tracking, increased stress on bearings
Damaged idlers/ rollers	Breakage and failing of idlers/ rollers, increasing friction, wear on belt, belt damage
Blocked rollers	Roller does not rotate, increased friction, heat generation/ overheating, damage to structure or belt
Conveyor belt	
Wear	Excessive wear, reduced rubber thickness, decreased strength and flexibility of the belt
Belt tracking	Uneven wear, increasing force on specific idlers/ rollers, increasing wear on edges, belt failure, increased stress on idlers bearings
Damaged rubber belt	Belt failure, belt tracking, friction, breakage
Tear in rubber	Larger tear, belt breakage
Splice issues	Belt breakage
Steel cords damage	Breakage of steel cords, belt failure, belt tear
Steel cords breakage	Idler damage, structure damage, belt damage, belt breakage
Slipping belt	Material spillage, belt failure/ damage, reduced efficiency
Emergency line pulled	Belt is stopped automatically
Melted rubber	Fire spreads, melting more rubber
Tensioning problems	Reduced efficiency, belt failure, material spillage
Electromotors	
Failing to start	No operation
Misalignment of shaft	Vibration, reduced efficiency, increased friction, motor damage, bearing damage
Bearing failure	Increased friction, heat generation, overheating
Overheating	Engine stop, fire, thermal stress, reduced electromotor life
Winding insulation failure	Short circuit, reduced efficiency, breakdown
Rotor/ stator failure	Reduced efficiency, motor failure
Vibration	Increased wear, friction, damage to other components, breakage of shaft
Contamination	Short circuits, friction, wear and damage to inside components
Oil leak	Increased wear and friction, bearing failure

Table 5.3: Effects per failure mode

Failure mode	Effects
Gearboxes	
Oil leak	Increased wear and friction, bearing failure
Gear wear	Reduced profile, reduced efficiency, gear slipping, backlash
Breakage of gear tooth	Loss of gear, damage to other components, breakdown
Overheating	Thermal stress, increased wear, damage to other components inside
Misalignment	Increased wear and friction on bearings and gears, reduced efficiency, bearing failure, gear tooth breakage
Vibration	Increased wear and friction on bearings and gears, damage to other components, breakage of gear, breakage of shaft
Housing damage	Lubrication issues such as leakage, structural weakness, breakage of housing
Gear tooth damage	Increased friction, gear tooth breakage
Backlash change	Reduced precision in motion transmission, increased noise, vibration, gear tooth breakage
Pulleys	
Bearing failure	Increased friction, heat generation/ overheating, breakage
Misalignment	Uneven wear on pulley, uneven wear on belt, increased stress on bearings, increasing belt wear, belt tracking
Wear	Belt slippage, decreasing pulley diameter, decreased or increased friction on the belt, belt damage
Material buildup	Increased friction, belt tracking, uneven wear
Slipping belt	Reduced efficiency, wear, belt damage
Blocked pulley	Pulley does not rotate, belt wear, overloading on electromotors and tensioners
Tensioning device	
Bearing failure	Increased friction, heat generation/ overheating, breakage
Misalignment	Uneven tension distribution, increased wear, belt tracking
Over tensioning	Increased stress and wear, belt tracking, belt damage, breakdown
Under tensioning	Slipping belt, increased wear, belt tracking
Failing to start	No operation
Counterweight failure	Unable to fulfill required tensioning demand, under tensioning, over tensioning, belt wear, belt damage
Wear	Excessive wear, decreased precision, increased friction, misalignment
Hydraulic or pneumatic issues	Reduced efficiency, loss of tensioning force, under tensioning
Structure/ frame	
Cracks	Larger cracks, tears
Tear	Breakage or collapse
Breakage	Collapse of the structure

Table 5.4: Effects per failure mode

5.5. Step 4: Identify causes

For every malfunction or failure mode, one or multiple causes exist. In tables 5.5 and 5.6 the failure modes with their respective causes can be found. The causes are based on EMO's database [16].

Failure mode	**Cause**
Idlers	
Bearing failure	Lack of lubrication, contamination, overloading
Overheating bearing	Bearing failure, increased friction, lack of lubrication
Damaged bearing	External loads from bulk material, other external forces, damaged idler
Misalignment in rollers	Improper installation, belt misalignment, damage to frame and structure
Damaged idlers/ rollers	Uneven load, external forces, wear, weather conditions, corrosion
Blocked rollers	Material buildup, broken bearing, steel cord wrapped around idler/ roller
Conveyor belt	
Wear	Friction, load from bulk material, external load, weather conditions, external forces
Belt tracking	Misalignment belt, misalignment idlers, damaged idlers, uneven loading, uneven structure, faulty settings, tensioning problems, pulley failure, uneven tension
Damaged rubber belt	Sharp pieces in load, uneven loads, damaged idlers, damaged pulleys, overloading, high impact, abrasive materials, friction
Tear in rubber	Sharp piece in load, lack of maintenance on puncture
Splice issues	Bad joint connection, improper splicing technique
Steel cords damage	Wear, corrosion, rubber failure/ damage in combination with weather conditions or corrosion
Steel cords breakage	Lack of maintenance on steel cords damage, sharp piece, abrassive materials
Slipping belt	Smooth pulley, tensioning not correct, contamination, weather conditions
Emergency line pulled	Birds chilling on the emergency line, colleague pulls line in case of emergency
Melted rubber	Fire from overheating bearing when belt is stopped
Tensioning problems	Problems with tensioner, slipping belt, contamination and friction
Electromotors	
Failing to start	Software issue, not connected
Misalignment of shaft	Lack of maintenance, improper installation, external forces
Bearing failure	Lack of lubricstion, contamination, misalignment, overloading
Overheating	Overloading, insufficient cooling, poor ventilation (if inside)
Winding insulation failure	Overheating, deterioration, voltage spikes
Rotor/ stator failure	Overheating, mechanical damage, manufacturing defect
Vibration	Misalignment, unbalanced loads, mechanical resonance, external forces, damage of bearing or other components
Contamination	Dust from bulk material, moisture, weather conditions
Oil leak	Damage to housing of lubricated parts, misalignment of lubricated parts

Table 5.5: Causes per failure mode

Failure mode	**Cause**
Gearboxes	
Oil leak	Damage to housing of lubricated parts, misalignment of lubricated parts, seal failure
Gear wear	Normal wear, misalignment
Breakage of gear tooth	Overloading, material defects, shock loads
Overheating	Overloading, insufficient cooling, excessive loads
Misalignment	Improper installation, manufacturing defect, external forces, overloading, thermal expansion
Vibration	Misalignment, imbalance, mechanical resonance, external forces, damage of bearing or other components
Housing damage	Material defects, overloading, shock loading
Gear tooth damage	Insufficient lubrication, contamination, excessive loads
Backlash change	Wear, misalignment, gear tooth damage
Pulleys	
Bearing failure	Lack of lubrication, contamination, overloading
Misalignment	Improper installation, belt misalignment, damage to frame and structure
Wear	Normal wear, weather conditions, abrassive materials, corrosion, friction with belt, alienated pieces in load
Material buildup	Weather conditions, material spillage, uneven loading, sticky belt, scraper not functioning properly
Slipping belt	Smoothened surface of pulley, wear, tensioning problems, contamination
Blocked pulley	Structure issue, broken shaft, material buildup, corrosion
Tensioning device	
Bearing failure	Lack of lubrication, contamination, overloading
Misalignment	Improper installation, belt misalignment, damage to frame and structure, external forces
Over tensioning	Software issue, incorrect parameters (manual or automated), faulty sensors, changing loads, unexpected changing conditions
Under tensioning	Software issue, incorrect parameters (manual or automated), faulty sensors, changing loads, unexpected changing conditions
Failing to start	Software issue, not connected
Counterweight failure	Mechanical failure, blockage
Wear	Normal usage, overloading, friction, weather conditions, environmental issues, corrosion
Hydraulic or pneumatic issues	Lack of lubrication, contamination, pressure loss, oil leaks
Structure/ frame	
Cracks	Wear, weather, uneven or heavy loads
Tear	Wear, weather, heavy loads
Breakage	Long period of wear, heavy loads, bad weather, environmental issues

Table 5.6: Causes per failure mode

5.6. Step 5: Determine risk priority numbers

The risk priority number (RPN) is a product of three parameters with their respective ratings for severity (S), occurrence (O) and detection (D). Each parameter has its own scale from 1 to 10, resulting in an overall risk priority number from 1 to 1000.

To be able to rank the criticality parameters from 1 to 10, a measurement scale is set up. The scale should span from the most severe consequence of interest to the most benign in case of severity. For occurrence the scale should span from lowest to highest likelihood. For detectability this should be from the lowest to the highest degree of detectability. This is done for all failure modes.

Detectability

The detectability scales from 1 to 10, where 1 has the highest possibility of detection and 10 has the lowest possibility of detection. This means the harder it is to detect a certain failure mode, the higher its risk priority number will be.

Rating	Detection
1	Almost certain
2	Very high/ very likely
3	High/ likely
4	Moderately high
5	Moderate
6	Low
7	Very low
8	Remote/ unlikely
9	Very remote/ very unlikely
10	Almost uncertain/ almost impossible

Table 5.7: Rating scale for detectability [65]

Some failure modes will be certainly detected because the automated system gets a signal and the operation might be automatically stopped. When the emergency line is pulled for example, it immediately stops the belt and sends a signal to the operators. Therefore, this specific failure mode will score 1 on detectability. Other failure modes may score differently because it will not automatically be detected. Sometimes it is required for a human worker to be present to visually see the failure mode, or hear or smell the effects of a certain failure mode. One experienced example is that - even with all the noise from equipment around - it was possible to hear that an idler was vibrating/ misaligned, while standing on the top of one of the quay cranes that was operating. When returning back on the ground, it was possible to follow the ticking sound and detect the faulty idler. At that moment the operator was notified and a decision was made to stop the belt and replace the idler.

Another example is when belt 171 caught fire because of an overheated bearing in an idler. This specific conveyor belt was located in a tunnel, so the fire would not immediately be visible to workers around. A human worker noticed smoke coming out of the end of the tunnel and when taking a look, he noticed the belt was on fire. In this specific case the detectability for this belt would be different for another belt that is out in the open air - as most conveyor belts are.

Occurrence

The occurrence is based on the causes of a failure mode and scales from 1 to 10, with 1 being the lowest occurrence and 10 the highest. A higher occurrence number results in a higher risk priority number for a failure mode that happens more often. It is also possible to base the occurrence rating on actual numbers. The mean time between failures can be used to design an occurrence ranking that fits the terminal. Instead of ”almost never” and ”low probability”, it could be described as a chance of failure per year, per operational hour, or per amount of operating cycles.

Rating	Occurrence
1	Almost never
2	Individual cases
3	Very rarely
4	Rarely
5	Low probability
6	Average
7	Quite high
8	High
9	Very high
10	Almost always

Table 5.8: Occurrence ratings [**FMECAminingexcavetor**]

Severity

The severity is based on the effects per failure mode. The more severe a failure mode's effects are, the higher the severity number will be. This results in a higher risk priority number as well. This table is accompanied with a more detailed description, to make the severity more understandable. This severity table was based on several journals and books [54] [11].

As discussed before, the severity might score differently for different conveyor belts. Some belts are more critical than others, because of possible rerouting possibilities. The quay conveyor belts (010, 020, 030 and 040) are more critical than the stacker-reclaimer conveyor belts (210, 220, 230, 240, 250, 260 and 270), simply because there are less quay belts than stacker-reclaimer belts. The quay belts are critical in the sense that they transport the bulk material to any other place at the terminal when it is unloaded from the vessels. If one regular belt on the terminal fails, it is most likely there is another route possible to transport the bulk material from the quay cranes to its supposed location.

Rating	Severity	Detailed description
1	Very minor	System is fully operational, no effect on system performance, not noticed by operator, no safety issues, no financial losses
2	Minor	System is fully operational, no safety issues, operation with minor side effects (i.e. noise), unlikely to be noticed
3	Very low	System is fully operational, insignificant physical damage, side effects (i.e. noise, vibrations), weak impact
4	Low	System is fully operational, minor physical damage, operation is accompanied by side effects, negligible impact
5	Moderate	Discernible influence
6	Moderately high	Considerable influence
7	High	Major impact
8	Very high	Acceptable impact
9	Critical	Very serious impact
10	Catastrophic	

Table 5.9: Severity ratings [65]

Based on the data from PowerBI, experiences at the terminal and other points of view from research papers, the occurrence, severity and detectability can be determined per failure mode. Some failure modes can vary in severity and will be explained here. The total values of the risk priority numbers will be shown in the following tables.

Taking a look at the conveyor belt's failure modes, the breakage of steel cords can vary in severity and detectability. For example, when one of the cords breaks, it will be hard to detect in the beginning. At this moment it might not even be as severe as the lower severity ratings since the system will be fully operational with insignificant physical damage. After a while, the broken cord will come loose from the belt and eventually could wrap itself around idlers or something else in its environment. At this moment, the loose cord has created a high severity and a high visual detectability. This does not mean it scores as a high detectability, because a human worker needs to be present. At the terminal of EMO B.V. there is no continuous visual surveillance for all the 27 kilometers of conveyor belt, therefore the detectability will be lower. This results in a higher risk priority number.

Another issue is when a component is failing to start. The severity might be a 10, because it is not able to operate, but the solution could be as simple as flipping a switch.

Failure in belt	S	O	D	RPN
Dent	1	6	10	60
Puncture	3-6	4	6	72-144
Tear	2-10	2-6	1-10	**
Loose cord	9	2	5-10	90-180
Belt tracking	1-3	9	1	9-27
Belt fire	10	2	1-10	20-200

Table 5.10: Example of risk priority numbers in several belt failure modes; ** the tear RPN is explained in the following table

Table 5.10 shows the different risk priority numbers for several failure modes. In this table, the last priority is belt tracking and the biggest could be belt fire. A fire is catastrophic, but does not occur very often. The detectability is depending on the location of the fire. As will be explained in the following chapter, a tunnel fire is hard to detect compared to a fire in the open air in the main area of the terminal, for example close to the office. The detectability is in this specific case also dependent on the weather (if it is dark outside, the fire might be easier to spot). This results in a variety of the risk priority numbers.

This table shows a variety in numbers for other failure modes too, as they can be divided in multiple severities. These different severity numbers might come with different values for occurrence and detectability as well, resulting in a wide variety of risk priority numbers. As an example, the malfunction "tear" is explored in table 5.11. The tear is divided into small, medium and large and is also split into two locations: on the edge or in the main part of the belt. A larger tear is more severe than a small one, but might have a lower occurrence but better detectability (which results in a lower detectability number). Similarly, a tear in the main part is more severe than one located close to the edge.

Failure in belt	S	O	D	RPN
Small tear on edge	2	6	9	108
Small tear in main part	3	5	9	135
Medium tear on edge	3	5	8	120
Medium tear in main part	5	4	8	160
Large tear on edge	8	3	8	192
Large tear in main part	10	2	8	160

Table 5.11: Example of tears in belt with their risk priority number

5.7. Step 6: Identify actions

With the gained knowledge it is possible to rank the failure modes from highest risk priority number to lowest. There will always be some risk that needs to be accepted, as it is nearly impossible to handle every single failure mode for all the equipment. The reliability engineers and human workers on site need to decide which levels of risk priority number are mild enough to take the risk and which risk priority numbers are high enough to take action. This can be divided in "taking immediate action" and

”taking action when operation is done”, or even ”take action at the next shift” or next week. This is all to be determined by the engineers responsible.

Keeping in mind that some conveyor belts are more critical than others, it makes sense to identify risk priority numbers per group of conveyor belts that have similar criticality. It is also possible that more critical conveyor belts already have better/ more surveillance or more sensors to detect some of the causes of failure modes. In that case, the values for severity, occurrence and detectability might be completely different. There is even a possibility that with different surveillance modes for different conveyor belts, the risk priority numbers are completely different and a high scoring failure mode for normal belts might not even be as severe for a critical belt! In the end, this might not be the case for the terminal of EMO B.V. as their equipment is quite similar for the entire terminal. It still is a good topic to discuss for future changes as the analysis need to be kept up to date. This will also be discussed in section 6.5.

Failure in belt	**RPN**	**Actions**
Dent	60	Continue operation
Tear	108-192	Repair if possible; prevent growing
Loose cord	90-180	Stop operation; remove cord
Belt tracking	9-27	Continue operation; check load distribution and belt placement

Table 5.12: Identified actions according to risk priority numbers

Figure 5.6: Belt damage: a tear and dent in belt 020 and a tear on the edge of the belt (16 Feb 2022) [16]

5.8. Conclusion

”How is this methodology implemented to create a new maintenance strategy and how is the maintenance strategy kept up to date?” With FMECA it is possible to investigate all possible malfunctions and address their cause and effect. With the risk priority number that is based on severity, occurrence and detectability, the malfunctions can be prioritized according to their criticality. This leads to a prioritized list of malfunctions that need to be handled. Eventually a database is created with every malfunction with their respective causes, effects and solutions. Whenever a new malfunction occurs, this must be added to the strategy along with its causes, effects, risk priority numbers and solutions. Even when an existing malfunction occurs, there is a possibility that there is a new cause, effect or solution. The strategy is kept up to date by continuously adding new information when it occurs. This strategy works best if kept up to date.

The new maintenance strategy works as follows (also shown in figure 5.7): Whenever a malfunction occurs, the belt must be stopped. Usually the belt is stopped automatically, but if this is not the case, it should be stopped manually. Data of the specific belt must be externally saved! When the failure mode is identified, check the causes, effects and actions. Perform the action if possible. If not possible, or if there is a new cause, effect, or failure mode; investigate the new situation and add this to the strategy. If possible, implement the failure mode and prevention into the software. Perform the desired action and continue operation. Document the malfunction and adjust the strategy if necessary.

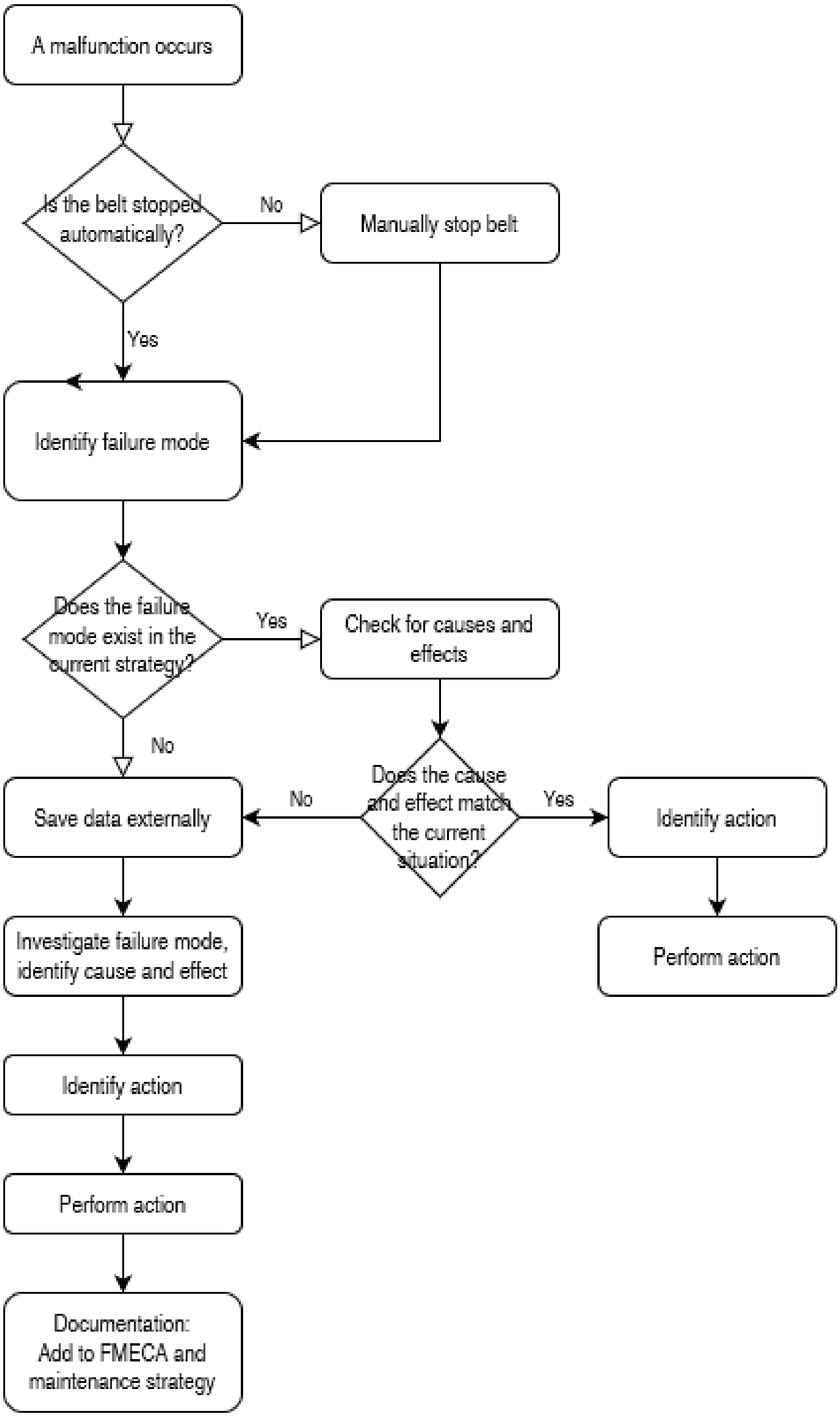


Figure 5.7: Flowchart of the new maintenance strategy with the FMECA method

6

Case studies: new maintenance strategy

This section will explain how small malfunctions can result in extreme failure consequences when left untreated by using three case studies as an example. These case studies were events that happened during the time this thesis was performed. The first section will explain failure consequences in general, where the three following sections will explain the three case studies. The last section concludes this chapter.

6.1. Failure consequences

Avoiding unplanned downtime

Avoiding unplanned downtime offers a range of beneficial outcomes for an industrial environment. By removing unplanned downtimes you prevent unplanned production delays which can lead to a loss of reputation if orders are not completed on time and the need to pay overtime to complete a job. In addition, there is no need to pay for an emergency call out to maintenance staff, which is more expensive than pre-scheduled maintenance [38].

Preventing more damage

A machine failure can cause damage in other systems, compounding the problem further while also increasing repair or replacement costs. As a result, there will be no need to buy and store large numbers of replacement assets or parts in case of an unexpected failure. Instead, you will be forewarned of the need to replace a part and can order it as required in time for scheduled maintenance[38].

Figure 6.1: Belt damage: a tear and dent in belt 020 and a tear on the edge of the belt (16 Feb 2022) [16]

Figure 6.2: Broken Stutzringroll on belt 010 (6 July 2022) [16]

Figure 6.3: Examples of contamination in idlers: Top three pictures taken on 22 Nov 2021, bottom three pictures taken on 16 Feb 2022 [16]

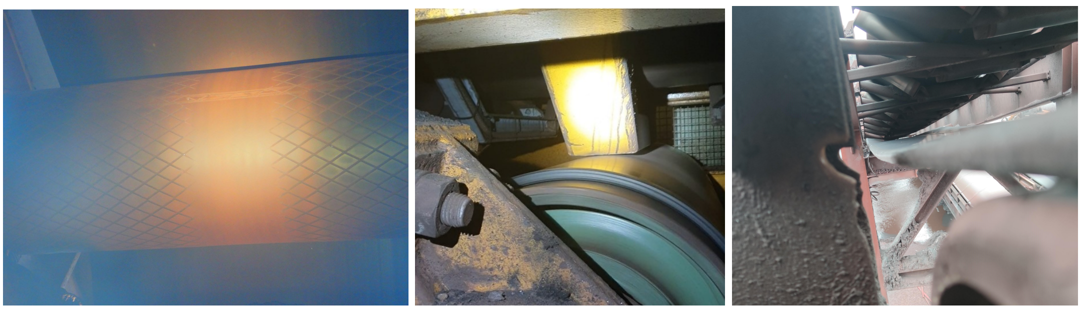


Figure 6.4: Examples from wear. Left picture shows a drum which is worn out in the middle part and became smooth. The remaining profile on the edges of the drum are still visible. Middle picture shows a piece of metal that runs into the belt, creating damage to the rubber (9 February 2022). The right picture shows a worn out structure where the returning belt has continuously run into the structure (16 February 2022)

6.2. Case study 1: Fire in belt 171

At January 31st 2022 around 22:00 a truck driver noticed smoke coming out of the tunnel of belt 171. The human worker notified the inhouse firefighters and the current operator, while In the mean time he started extinguishing the fire by himself. Whenever there is a possibility for fire expansion, not only the company's firefighters are called in, but the collaborating firefighters from the Maasvlakte are called in as well. When the collaborating firefighters arrived, the fire was already under control.

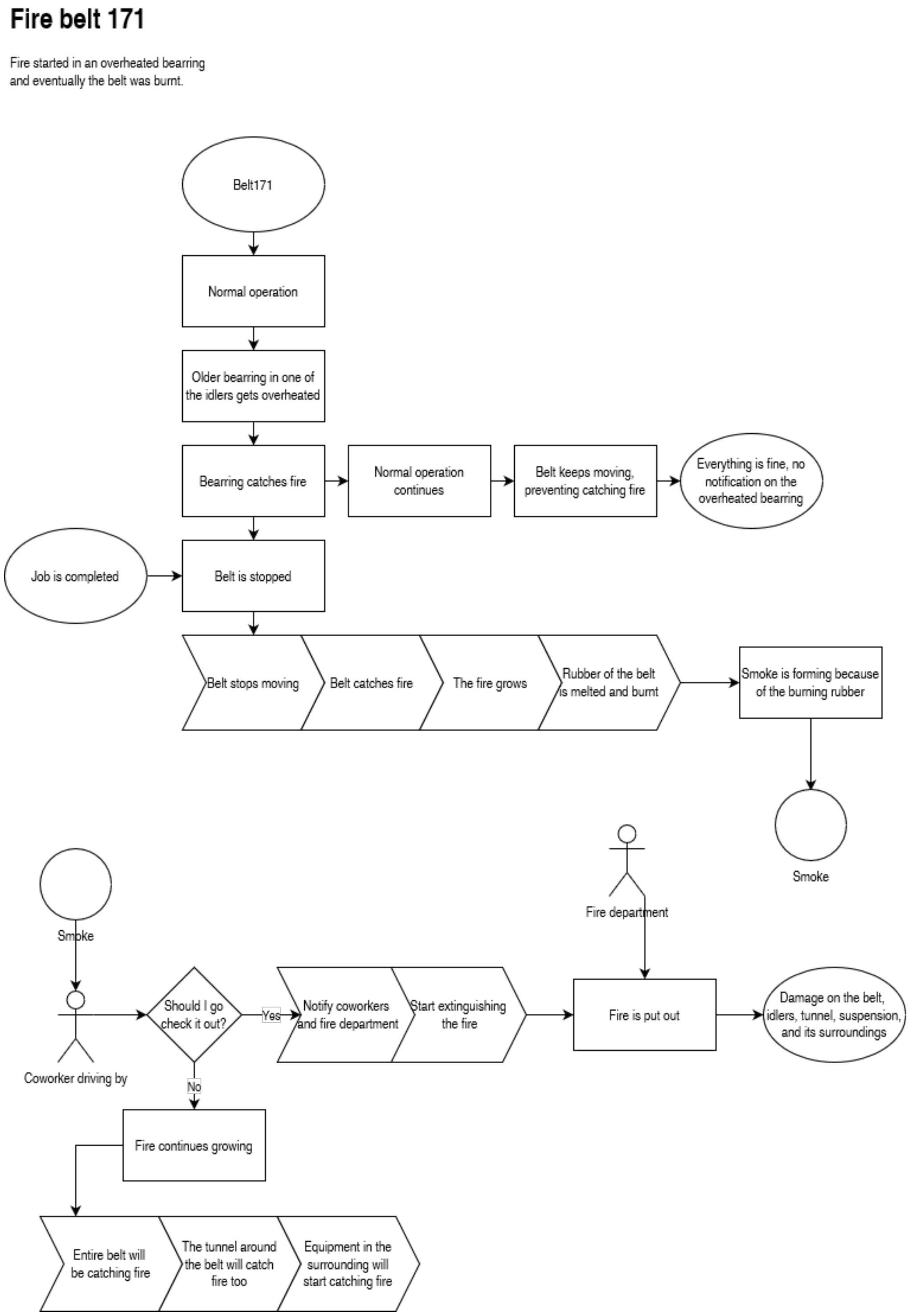


Figure 6.5: Flow chart diagram of case study 1

Cause

It turned out there was an overheated bearing in one of the idlers of the belt. During operation the belt does not have a chance to catch fire, because the belt runs with 4.5 m/s along this specific idler. But, after the operation was done and the belt was empty, the belt was stopped and the local heat development around that bearing was able to set fire to the belt.

Effects

The fire was caught in an early stage, preventing more damage from happening. The fire did not spread to other conveyor belt systems or other equipment. Some of the surrounding pipes were partially melted but managed to protect the cables inside. The conveyor belt structure had no damage, but 151 meters of belt 171 needs to be replaced. To connect this new part to the old part of the belt, another company (Narviflex) is hired to make the two junctions. A scaffolding is built up for the company to work the belt safely. Whenever a part of the belt is replaced, the tension must come off and has to be readjusted afterwards. In order to do this for belt 171, a 450 ton crane is required to lift the Hampelman counterweight. The weighing installation and electronic cables around are damaged. The cables will be replaced and new load cells were placed. This all requires testing and calibration and takes some time.

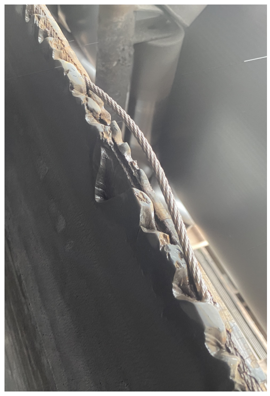


Figure 6.6: Loose steel cords on the edge of the belt (picture taken 1 February 2022)

Actions

After testing the belt and inspecting it, then testing it again and letting it run for about 45 minutes without any problems, the belt was ready for operation again. In total the belt needed five days to be repaired. Two outside companies were required for this reparation and the firefighters were called in. Some pipes, cables and idlers needed to be replaced. 151 meters of the belt was replaced as well. Total cost: €72.691,53.

Figure 6.7: Pictures of the fire in belt 171: Left picture with fire, right picture shows the steel cords after extinguishing (rubber melted). Both pictures taken on 31 January 2022 [16]

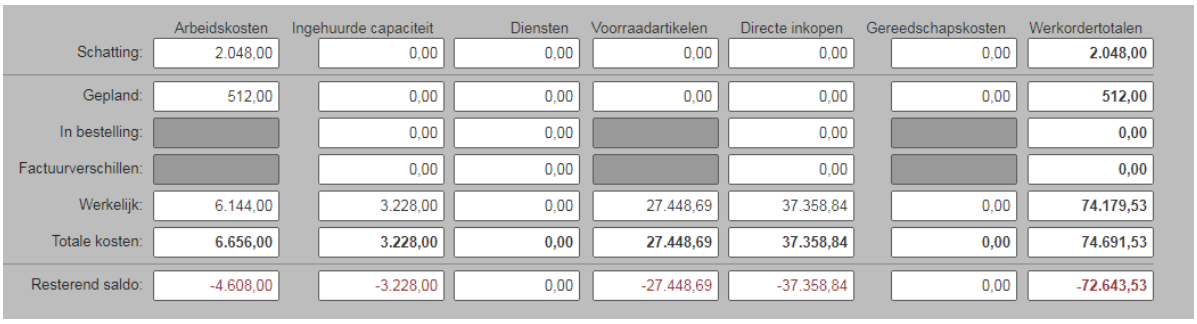
Conclusion

This case study shows that there must be supervision at less visible and unmanned locations, like tunnels or conveyor belts far away. This time the fire was caught relatively early, because a driver was passing by, handling the fire himself immediately. Next time the fire might be caught in a later stadium, maybe unable to be extinguished or with much larger consequences and damage.

A possibility to have more supervision in unmanned locations is placing (infrared) cameras. The downside is, that this requires human operators to look at those cameras consistently. A better solution therefore might be infrared sensors that activate a trigger warning above a certain threshold. When there are cameras placed nearby, the operator can check via camera if the warning is legit. In case it is, the operator can warn the firefighters or activate sprinklers in the area. Most conveyor belts have sprinklers installed already because of dust prevention. After some successful testing this threshold can be build into the software and even be automated. Important is to do this after testing multiple times, to prevent unnecessary extinguishing sessions, which could also harm the equipment.

Failure mode	**Belt 171 caught fire**
Cause	Overheated bearing in idler
Effect	Set fire to belt 171 after the belt was stopped
Notified how	A truck driver passing by
Solved how	First the truck driver warned the operator and inhouse firefighters Then the truck driver started extinghuishing the fire himself Inhouse firefighters take over Outside firefighters arrive after fire is under control
Damage	151 meters of belt need to be replaced The weighing installation requires new load cells and cables Surrounding cable pipes melted; need to be replaced (these cables were not harmed)
Downtime	5 days (January 31st 22:00 - February 5th 18:00)
Cost	€72.691,53

Table 6.1: Worksheet of event of belt 171 [16]



	Arbeidskosten	Ingehuurde capaciteit	Diensten	Voorraadartikelen	Directe inkopen	Gereedschapskosten	Werkordertotalen
Schatting:	2.048,00	0,00	0,00	0,00	0,00	0,00	**2.048,00**
Gepland:	512,00	0,00	0,00	0,00	0,00	0,00	**512,00**
In bestelling:		0,00	0,00		0,00		**0,00**
Factuurverschillen:		0,00	0,00		0,00		**0,00**
Werkelijk:	6.144,00	3.228,00	0,00	27.448,69	37.358,84	0,00	**74.179,53**
Totale kosten:	**6.656,00**	**3.228,00**	**0,00**	**27.448,69**	**37.358,84**	**0,00**	**74.691,53**
Resterend saldo:	-4.608,00	-3.228,00	0,00	-27.448,69	-37.358,84	0,00	**-72.643,53**

Figure 6.8: Cost of repair 171

The flowchart of figure 6.9 shows the proposed solution with infrared sensors. When the sensor measures a value above the threshold, a warning will be sent to the operator. A pop-up is shown with live camera images where the operator can decide whether the warning is legit, not legit, or if a human operator must check on site for more information. When the warning is legit a decision can be made to activate the sprinkler system or to send firefighters to get the situation under control. When a bearing is overheated, it is important to keep the belt running to prevent it from catching fire. The belt must then be stopped only with supervision from firefighters on site.

Proposed solution

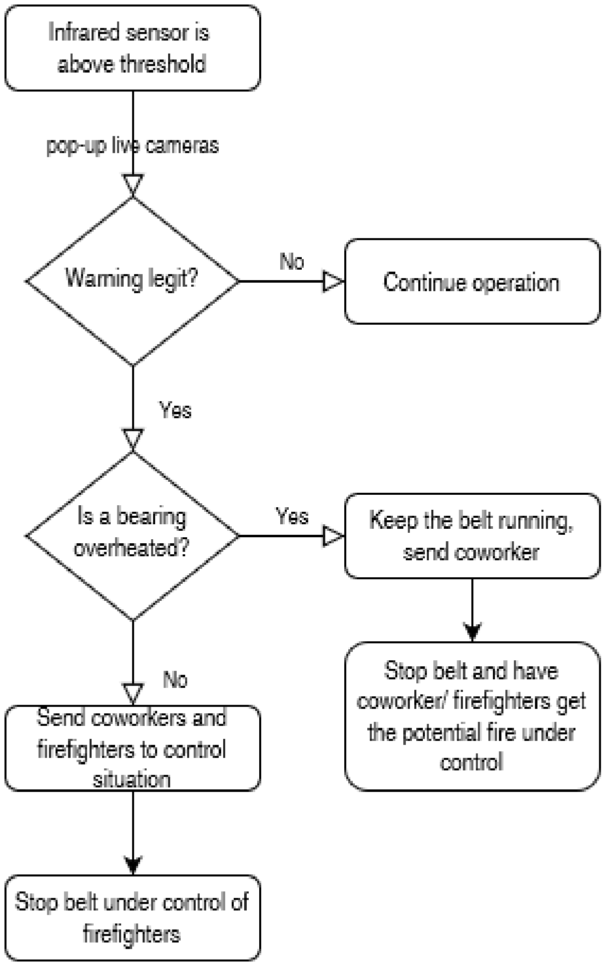


Figure 6.9: Flowchart of proposed solution

6.3. Case study 2: Tear in belt 240

In the night of February 9 to 10, belt 240 got spliced in half by a still unknown reason. The belt was probably damaged by a sharp large piece of metal or a sharp large stone, which had torn the belt and spliced it in half over 1600 meters. Two months later, the cause for this damage is still unknown. In figure 6.11 a few pictures are shown of the tear in belt 240. The left pictures show a close-up of the tear where a steel cord also came loose, also showing the build-up of dry bulk material below the idlers. The bottom right picture shows more of the build-up and a larger rock which came along with the load. The top right picture shows a large part of the belt split in half, where both halves lay on top of each other.

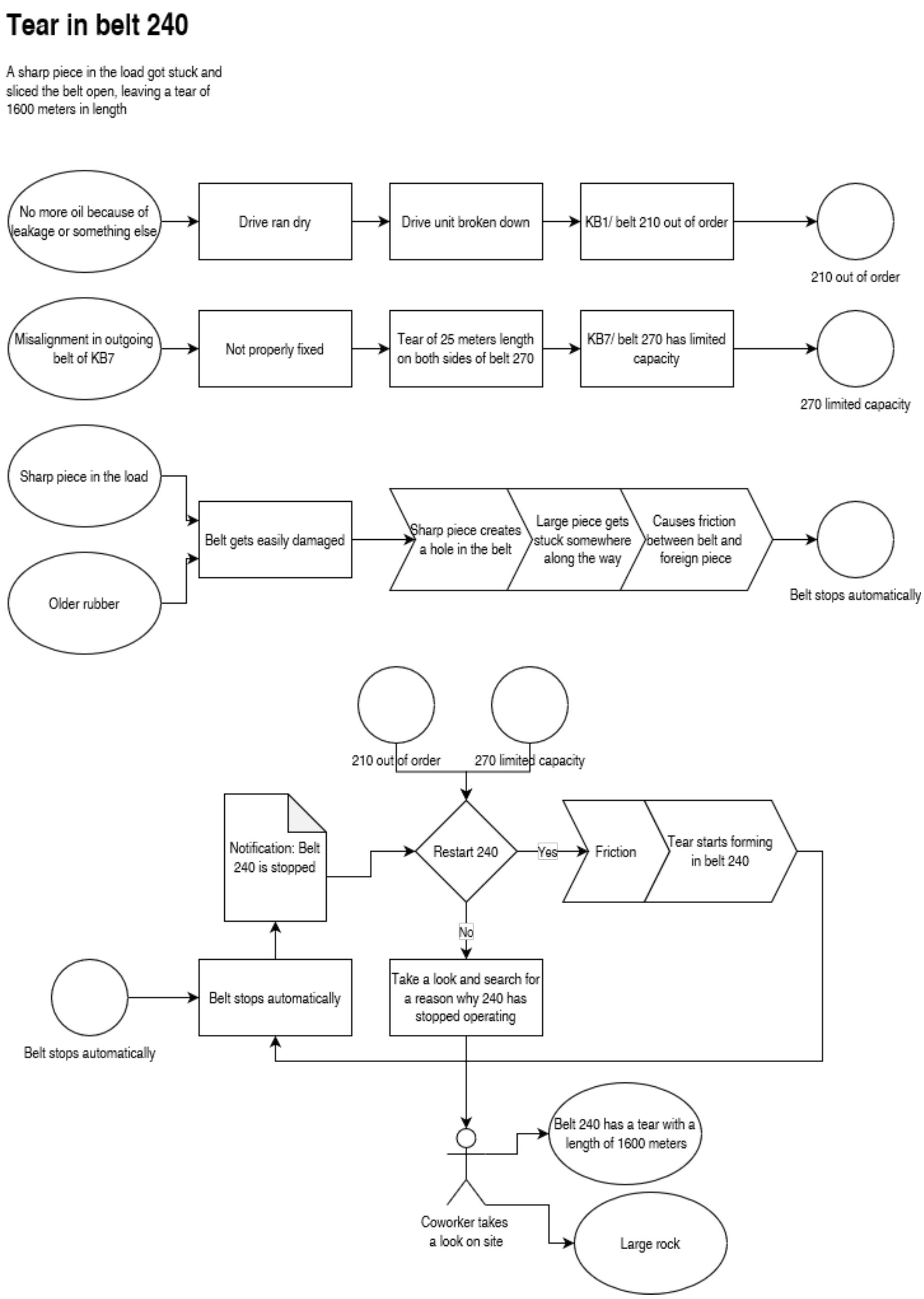


Figure 6.10: Flow chart diagram of case study 2

Figure 6.11: Tear in the belt 240, pictures taken on 10 Feb 2022 [16]. Top and bottom left: close-up of tear, where steel cord came loose. Top right: belt split in half, halves lay on top of each other. Bottom right: spillage and build-up material, larger rock which came along with the load

Cause and effects

Belt 240 was automatically stopped because of belt tracking. After several attempts to start the belt from the control room, the belt stopped itself every time after a short interval. After inspection on site a tear was discovered in the belt. A thorough inspection revealed a 1600 meter tear, but no immediate cause was found. The belt was stopped and the remaining bulk material on the belt was unloaded the day after (February 11) at a 25% speed. During operation the belt runs at a standard speed of 4.5 m/s, which means that it takes 355 seconds - almost six minutes - to damage the belt over a length of 1600 meters. Eventually the belt was not operable for 30 days and 3.5 hours (February 10 12:34 – March 2 16:07).

Actions

The belt was spliced in half over 1600 meters. This replacement reduced the belt stock of EMO B.V. by more than 50%. For replacing this part of the belt, Narviflex and Peineman are called in for making junctions and for transportation of the large pieces of rubber. The waterworks around the belt needed to be repaired as well. This came to a total cost of €372.887,09.

Traces in detail

Taking a look at the power output data, it can be seen in figure 6.12 that the power output was scattering more (larger peaks) over time. It also can be seen in figure 6.13 that for a certain time the direction of the belt changed. This is shown by the switching of the power output of the engines. As a reference a regular start-up and stop of the same conveyor belt is shown in figure 6.14 from the day before the event.

The red lines indicate the drive unit 1 (M11) and the purple lines indicate drive unit 3 (M21). Underneath the red line there is also a green line representing drive unit 2 (M12) and underneath the purple line there is a yellow line representing drive unit 4 (M22). Normally the drive units on the head side of the belt have a higher power output than the drive units on the tail end of the belt in a relation of 3:2. When the belt changes direction, this means that head and tail of the belt also switch; resulting in a change of power output. A change in direction is only done after the belt is stopped to prevent components getting damaged. In figure 6.12 is shown that the belt switches direction around 23:46 because of the change in power output (higher power output in drive unit 1 on the left side of the graph (before 23:46) versus lower output in drive unit 1 on the right side of the graph (after 23:46)).

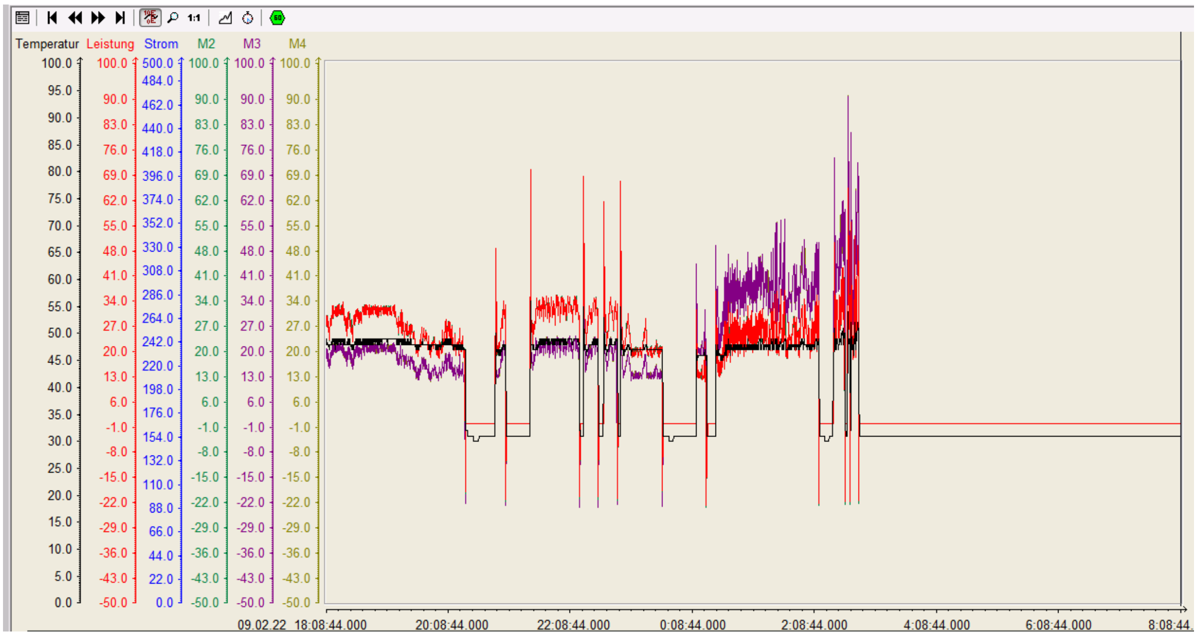


Figure 6.12: Scattering of power output for belt 240, screenshot taken at 9 February 2022. Red line indicates the power output of drive unit 1, purple line indicates the power output of drive unit 3. When the belt changes direction the drive units switch in high and low power outputs.

Looking back in all the data of the previous two weeks of the same belt (and also other belts), this amount of scattering was not found. In this particular case the power output goes up to 90% of its maximum output, where its regular power output should be around 34%. At the first scattering section between 0:34 and 2:17 there is an increase in power output around 40%. A small increase in power output is not directly bad, it could be because of a heavier load. But whenever the power output drastically increases, this indicates something else might be happening. In this particular case the scattering keeps increasing with peaks going from 27% to 90% (not including start-up and stopping, since that gives a peak in the power output as well, as can be seen in figure 6.14). It is possible to alert the operator when the scattering increases. For example, if the power output increases by more than 30% or if the power output reaches 60% of its maximum power, the software can send a warning to the operator. A pop-up with the live traces can be given and the belt can be automatically or manually stopped. A coworker will be notified by the operator to check on site and after successful testing this can all be automated.

In figure 6.13 a switch of power outputs can be seen around 2:49. Drive unit 1 and 3 switch in power output values, indicating a change in direction of the belt. Normally this does not happen during operation. All traces of belt 240 from before this event were looked into and no other direct switching during operation happened. It is possible to alert the operator with a warning when this happens, adding a pop-up screen with the live traces. This must be tested and can then be implemented in the software, preventing larger consequences like this 1600 meter tear from happening.

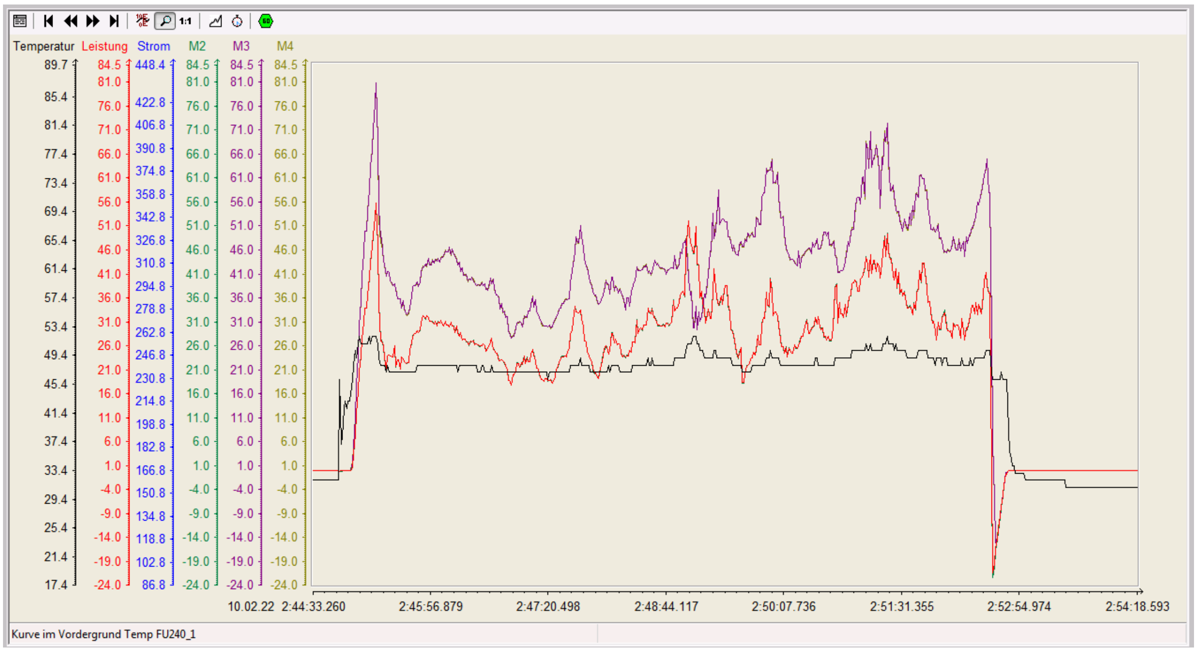


Figure 6.13: Irregular start-up and stopping of belt 240. Around 2:49 the power outputs of the head and tail drive units switch, indicating a direction change of the belt

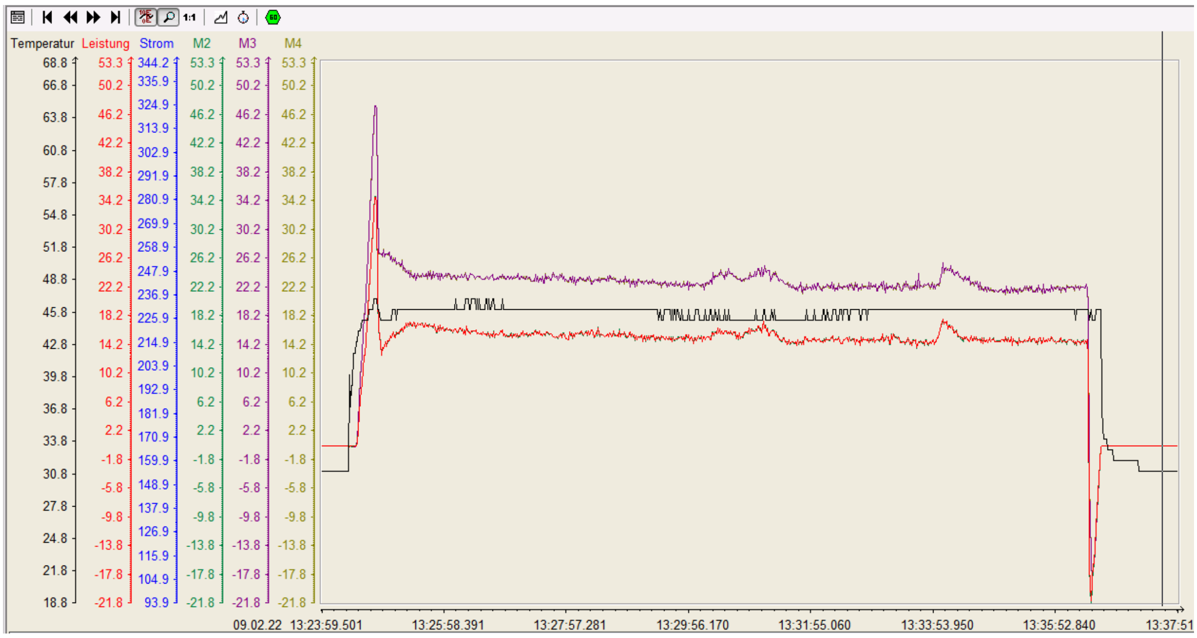


Figure 6.14: Regular start-up and stop of belt under normal circumstances, screenshot taken at 9 February 2022. Red line indicate drive unit 1 at the head of the conveyor belt, purple line indicates drive unit 3 and the tail of the conveyor belt

Conclusion

The belt was automatically stopped for many times. Belt 210 was already out of order because the drive unit was broken down because of an oil leakage. Belt 270 had limited capacity because of a misalignment in the outgoing belt. When belt 240 was consistently stopped automatically, the operator kept starting the belt, not knowing the actual issue. It happens more often that the belt stops automatically while nothing is wrong and considering two other belts are limited/ not working, the decision was made to start belt 240 over and over again.

Handling a similar event in the future must be done as follows: When extreme and irregular scattering occurs in the power output, check on-site for irregularities. When the power keeps increasing this could be because of the belt getting stuck. In this case, the power increased by 40%. It is possible to implement a warning in the software that is triggered when the power increases over a certain threshold. It must be made clear this is not in the startup phase of the belt, because then the power must increase.

It is not possible to add more screens and data at the operating room, as the operators already have more than 8 screens to look at during operation. But when there is a warning, it should be possible for the operators to switch to this data screen. Another possibility is installing more cameras and adding that to this screen as well. As smart as this solutions seems to be, it is very hard to get 3.5 kilometers of rubber belt into a 24 inch screen.

Failure mode	**1600 meter tear in belt 240**
Cause	Probably a sharp or large piece of metal/ stone
Effect	Teared belt 240 in half over 1600 meters
Notified how	Inspection after the belt was stopped several times
Solved how	Stopping the belt - setting up a maintenance plan
Damage	1600 meter belt need to be replaced
Downtime	30+ days
Cost	€372.887,09

Table 6.2: Worksheet of event of belt 240

	Arbeidskosten	Ingehuurde capaciteit	Diensten	Voorraadartikelen	Directe inkopen	Gereedschapskosten	Werkordertotalen
Schatting:	256,00	0,00	0,00	0,00	0,00	0,00	**256,00**
Gepland:	0,00	0,00	0,00	0,00	0,00	0,00	**0,00**
In bestelling:		0,00	0,00		0,00		**0,00**
Factuurverschillen:		0,00	0,00		0,00		**0,00**
Werkelijk:	14.720,00	13.845,00	0,00	247.529,27	96.792,82	0,00	**372.887,09**
Totale kosten:	**14.720,00**	**13.845,00**	**0,00**	**247.529,27**	**96.792,82**	**0,00**	**372.887,09**
Resterend saldo:	-14.464,00	-13.845,00	0,00	-247.529,27	-96.792,82	0,00	**-372.631,09**

Figure 6.15: Cost of repair 240 [16]

Proposed solutions

- If the power output increases by *x %* in *y seconds* (not including start-up and stopping): send warning to operator; pop-up with live traces; stop belt; send coworker; continue operation or maintenance (figure 6.16)

- Power output reaches threshold (value in %): send warning to operator; stop belt; send coworker to check on site; continue operation or maintenance (figure 6.16)

- Head and tail drive units switch power outputs during operation: send warning to operator; stop belt; send coworker to check on site; continue operation or maintenance (figure 6.17)

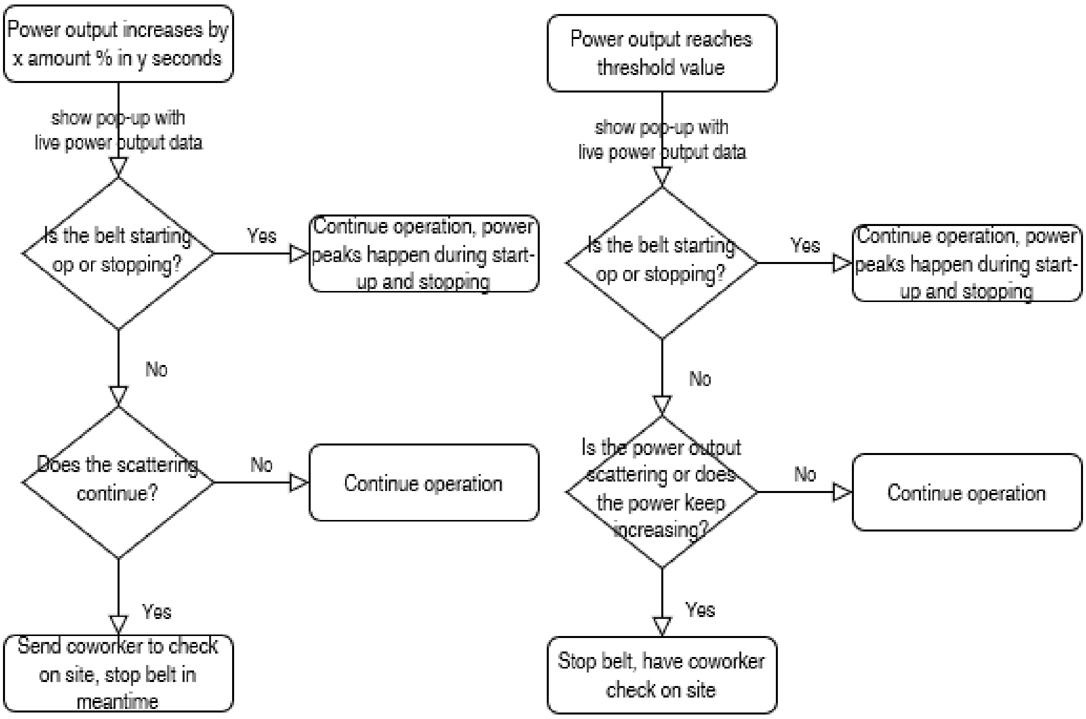


Figure 6.16

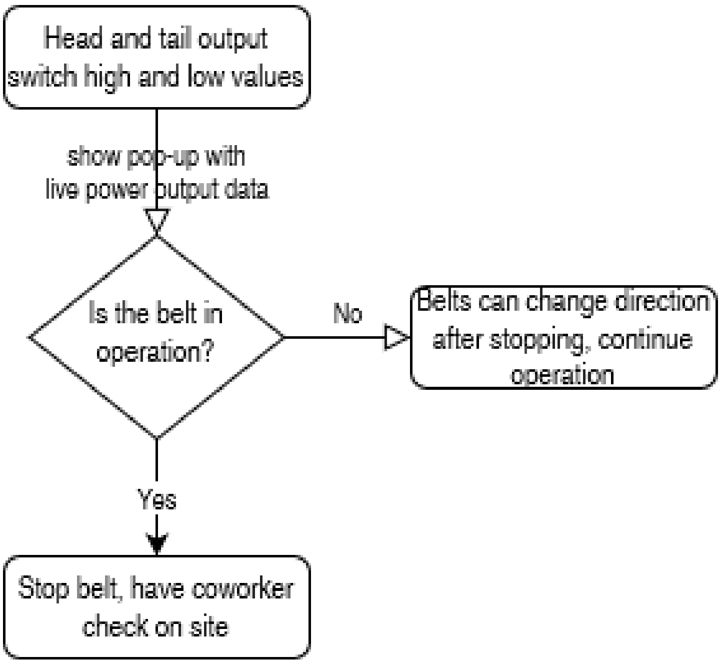


Figure 6.17

6.4. Case study 3: Broken axle in drive unit of belt 030

In the night of 22 July at 2:13 AM the axle of one of the drive units of belt 030 broke. This happened after the connection between engine and gearbox came loose. This was noticed by inspection as well as a grinding sound in the gearbox and a decision was made to empty the belt and continue with three drive units instead of four. After four minutes the axle between the gearbox and drum broke.

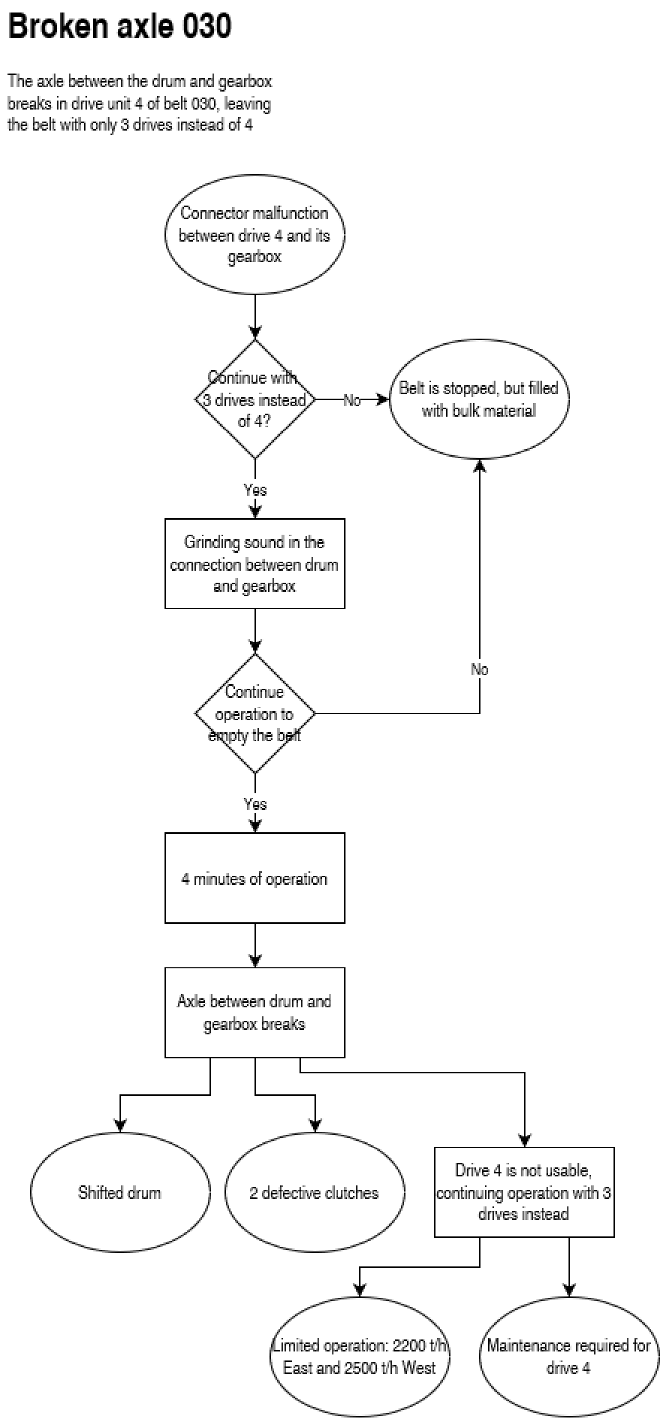


Figure 6.18: Flow chart diagram of case study 3

Effects

After a thorough inspection it was clear the belt could no longer operate with four drive units. This means that when the belt is able to operate again, the belt will have a limited work load in both directions. The fourth drive unit must be secured to prevent further damage. Several tests were done to ensure safe operation. The belt ran for four hours, while temperature of bearings and gearboxes were being checked with a FLIR camera. No problems were found during these tests, so the belt was able to operate with limited working load (2200 ton/hr in East direction and 2500 ton/hr in West direction).

Cause

In the traces is found that after the axle broke the belt was running for 15 more minutes. After this period the operator tried to start the belt again for about ten times. This could (and should) have been prevented. While the 030 belt was running at 4.5 m/s with coal the axle of drive unit 4 broke in half. The belt kept running as well as the drives. In the traces was found the exact moment where the axle broke. This can be seen by different factors:

- N4 suddenly goes up in value, N3 does not follow
- T4 drops to 0.0
- T3 goes up to twice its value
- Winch pressure suddenly goes up
- P4 drops to 0.0

When engine 4 suddenly runs more cycles per minute without engine 3 doing the same thing, this means that engine 4 is running freely. There is no friction anymore. As a result engine 4 does not deliver any more power (P4) and torque (T4). To compensate for the missing torque, engine 3 delivers twice as much torque as it did before.

The pressure in the winch grows extremely fast in a very short amount of time, therefore the software tells the winch to slow down (shown by the downwards peak of NrefSpl, which is the RPM reference value of the winch) to get the tension down to its desired value (DynSpSpl = dynamic set point value of the tension in the winch).

Even if a sensor was failing, there were other sensors working to check if engine 4 was failing or that it was only its sensor failing.

Action

After the axle broke, a decision was made to continue operation with three drive units instead of four. Two couplings were broken and a new drive unit was not immediately available. The axle was welded shut to prevent the coupling from sliding off the axle. The gearbox was secured to prevent it from damaging the coupling. With three drive units the operation was continued. After several tests to see if this operation was save, the belt 030 was released for limited operation (2200 ton/hr in East direction and 2500 ton/hr in West direction).

Traces in detail

The first picture of figure 6.19 shows regular operation in the left part, before 13:00. The right part shows irregularities. The second picture zooms in on the irregular part of the graph. As can be seen around 2:14 something happens. In figure 6.20 a close-up of this part is shown.

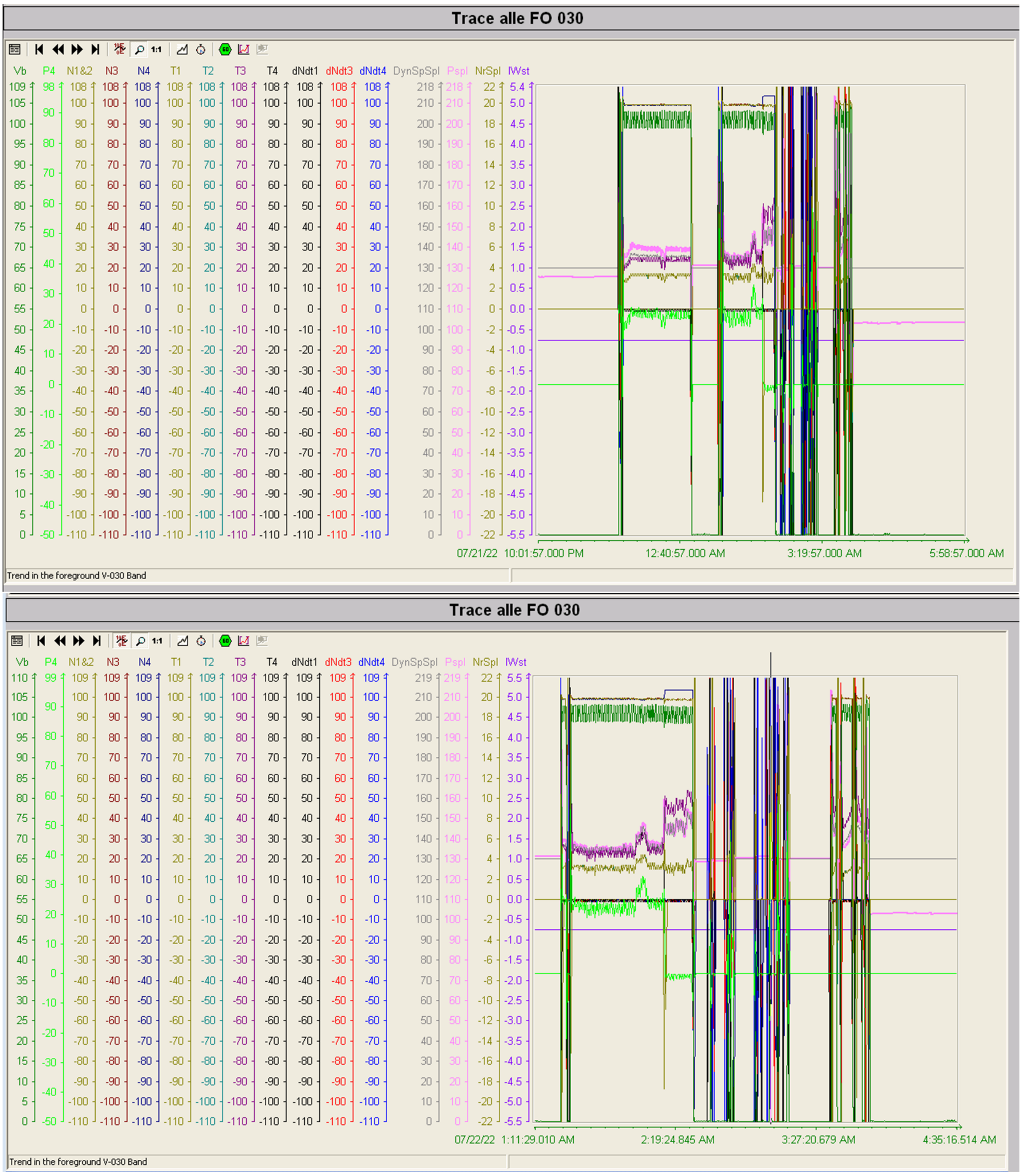


Figure 6.19: Traces screenshots with regular operation on the left part of the top picture and showing irregularities on the right part of the graph. Bottom picture is a close-up of the irregular part of the graph

Just before the event at 2:14 (top picture) the values of the torque for unit 1 and 2 are the same (18.0) as well as for unit 3 and 4 (26.0). The bottom picture is a bit zoomed in further and the values after the event at 2:14 are shown. The torque values of unit 1 and 2 are the same (14.0), while the torque values for unit 3 and 4 are different (43.0 and 0.0). The top red circle also shows that the rpm of unit 4 goes up to 103.4, while the rpm of unit 3 remains 99.0. The neon green line represents the power of drive unit 4 and it can be seen that this drops to zero when the malfunction occurs. Figure 6.21 shows a close-up of the rpm of drive unit 4 suddenly going up, with the values indicating the state before the event. The middle picture shows the values after the event. The bottom picture of this figure shows an overview with the important points in time marked (2:14 malfunction; 2:30 belt stopped; 3:15 belt not restarted anymore).

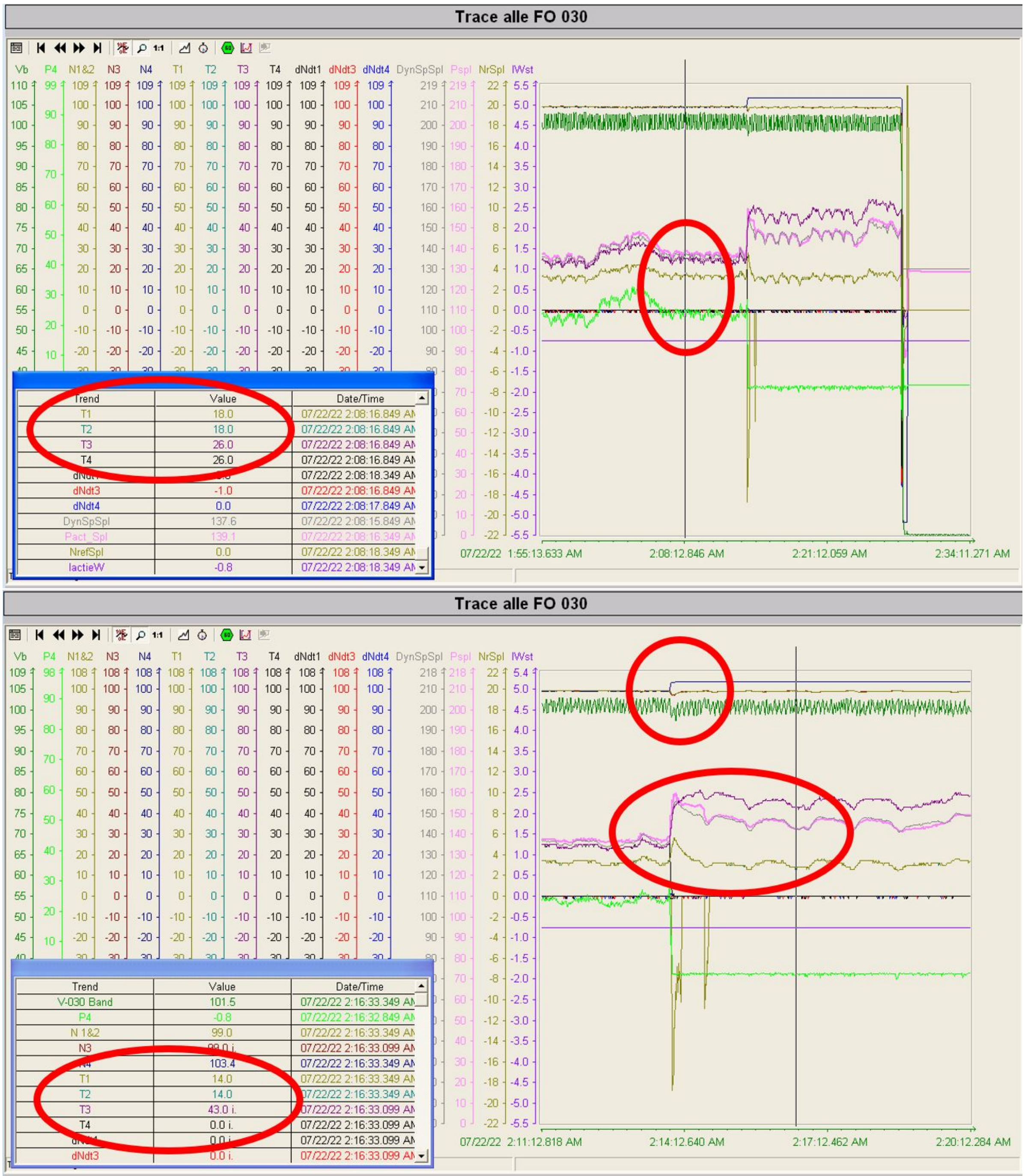


Figure 6.20: Close-up images with corresponding parameter values just before and after the event at 2:14

Figure 6.21: Top and middle pictures show a close-up of the rpm values of the four drive units with respective values before and after the event. Bottom picture is an overview with time notations

Conclusion

Next time it is important that when a similar situation occurs and an axle breaks, the operation must be halted. In this particular event this was not the case and the belt kept running for another 15 minutes, causing more damage to the gearbox of the engine. After the belt stopped itself, the operators tried to start the belt again for another 10 times, also not improving the state of the engine's gearbox.

	Arbeidskosten	Ingehuurde capaciteit	Diensten	Voorraadartikelen	Directe inkopen	Gereedschapskosten	Werkordertotalen
Schatting:	3.328,00	0,00	0,00	0,00	0,00	0,00	**3.328,00**
Gepland:	0,00	0,00	0,00	0,00	0,00	0,00	**0,00**
In bestelling:		0,00	0,00		884,00		**884,00**
Factuurverschillen:		0,00	0,00		0,00		**0,00**
Werkelijk:	29.440,00	6.585,98	0,00	19.009,75	50.224,03	0,00	**105.259,76**
Totale kosten:	**29.440,00**	**6.585,98**	**0,00**	**19.009,75**	**51.108,03**	**0,00**	**106.143,76**
Resterend saldo:	-26.112,00	-6.585,98	0,00	-19.009,75	-51.108,03	0,00	**-102.815,76**

Figure 6.22: Cost of repair 030 [16]

Failure mode	**Broken axle in drive unit 4 of belt 030**
Cause	
Effect	Limited operation; drive unit 4 is no longer available
Notified how	By inspection after the belt stopped automatically several times
Solved how	Continuing operation with three drives instead of four
Damage	Axle of drive unit 4 is broken Several couplings in drive unit 4 are damaged/ broken Limited operation in both directions
Downtime	1 day of maintenance to continue with limited operation Unknown amount of time for replacement of drive unit 4
Cost	€102.815,76

Table 6.3: Worksheet of event of belt 030

Proposed solution

A proposed solution is when one of the following rules happen, that the belt must be stopped. Another solution where faulty sensors are taken into account is that any two of the following rules happen. In the flowcharts of the proposed solution shown in figure 6.23, 6.24 and 6.25,the faulty sensors are taken into account, meaning that if any two events happen simultaneously, the belt must be stopped immediately. If two of these rules happen at the same time, it is unlikely both sensors fail and it is more likely something is wrong.

- If the rpm of one drive unit increases while its master-slave combined drive unit doesn't follow: stop belt (figure 6.23)

- If torque of one drive unit drops to zero and its master/ slave drive unit increases to twice its value: stop belt (figure 6.24)

- When the power of a drive unit drops to zero: stop belt (figure 6.23)

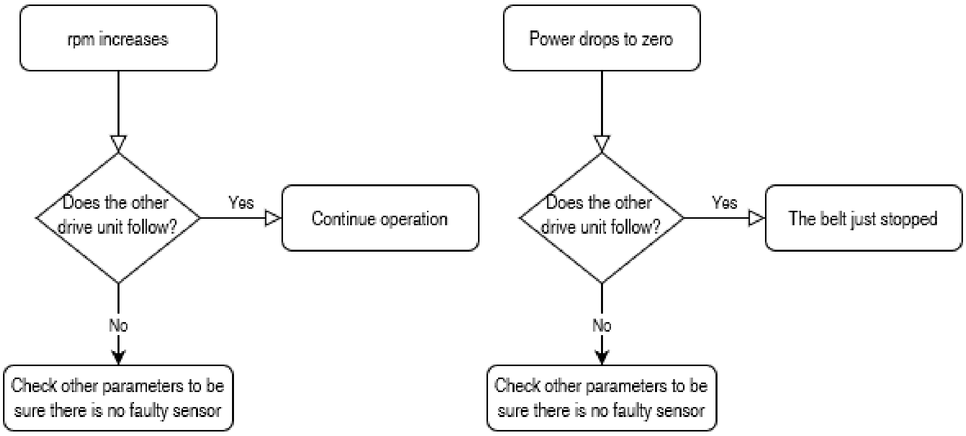


Figure 6.23: Proposed solution 030: Left flowchart: rpm increases. Right flowchart: power output drops to zero

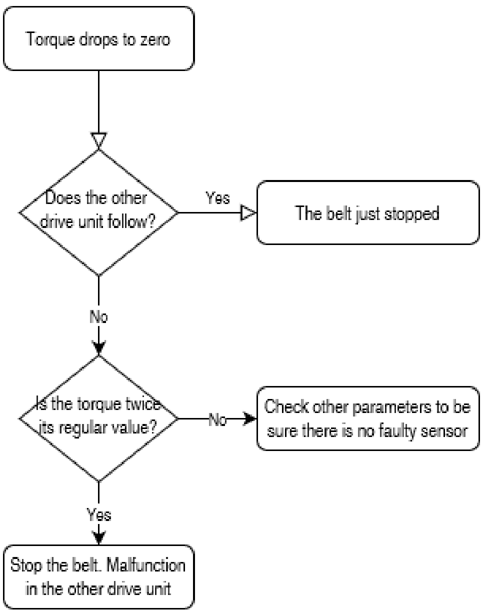


Figure 6.24: Proposed solution 030: Torque of one drive unit drops to zero

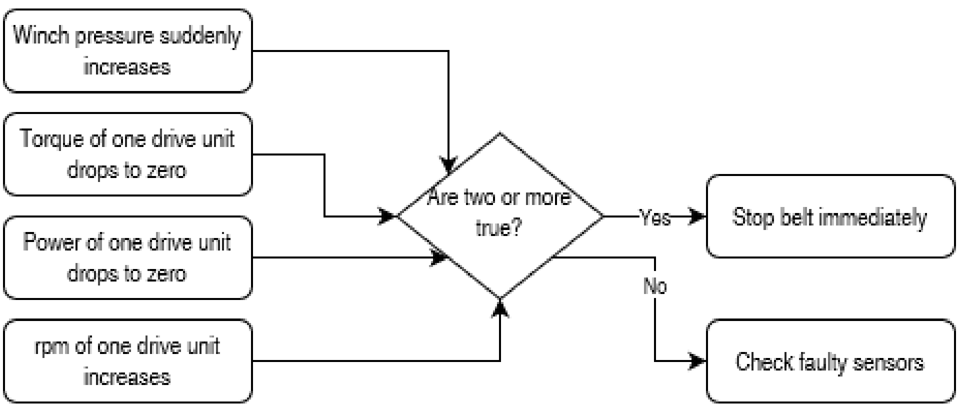


Figure 6.25: Taken faulty sensors into account for proposed solution 030

6.5. Conclusion

The three case studies show that the proposed maintenance strategy works. The first case study - where belt 171 caught fire in the tunnel because of an overheated bearing in an idler - shows that there must be supervision at ”invisible” and unmanned locations, like tunnels or conveyor belts far away. This time the fire was caught relatively early, because a driver was passing by, handling the fire himself immediately. Next time the fire might be caught in a later stadium, maybe unable to extinguish or with much larger consequences and damage. Solutions might come in the form of infrared sensors and automated sprinkler systems, or a trigger warning in the control room where the operator checks the cameras on site and alarms the firefighters (and activates sprinklers) if necessary.

The second case study - 1600 meter tear in belt 240 - shows that if the conveyor belt system automatically stops a lot of times, something might be wrong. From this specific event is learnt that when scattering of the power output keeps increasing, there might be something wrong with the belt itself. In this case probably a sharp or large piece came along with the load and ripped the belt open. This piece got stuck and spliced the belt in half over 1600 meters. The power peaks kept increasing in this specific case and in all the other data there was no scattering found like in the data of this belt at the moment of splicing. In the software a warning can be implemented that whenever scattering like this occurs after startup, when the power peaks increase over 40%, that someone must check on site if the belt is in good condition. As this was the only case that lead to this outcome, this scattering and the threshold of the increasing of the power peaks must be tested. When a warning is implemented in the software, the operator is able to alert a coworker to check on site. When everything is fine, the threshold must be further investigated.

The third case study - where the axle broke on the drive unit in belt 030 - has the most clear data traces. There are multiple parameters that show a malfunction. Whenever a drive unit is increasing or decreasing, its twin must follow. For the conveyor belt systems, the drive units work together as a master-slave combination. In this specific case the rpm of drive unit 4 increases, while the rpm of drive unit 3 does not follow. This indicates that there is no friction left and the drive is running freely. The torque of drive unit 4 drops to zero, while the torque of drive unit 3 becomes twice as high to compensate for the non-operating drive unit 4. This also indicates that the drive unit 4 is not operating and that number 3 is working twice as hard to deliver the desired torque. The power of drive unit 4 drops to zero as well and the winch pressure goes up. All these parameters indicate that drive unit 4 is not working anymore. It is of course possible that a sensor is faulty, but having 5 parameters telling the same story definitely indicates a faulty drive unit. This can be implemented in the software as follows: Whenever one torque drops to zero while its master-slave combined drive increases to twice its value; a drive unit stopped working. This in combination with the power dropping to zero of the same drive unit, the rpm increasing (running freely), indicates that the drive unit stopped working. The belt must be stopped immediately and operation must only be continued after thorough inspection of the drive unit.

Conclusion

This chapter will answer the main research question with the help of the answers to the sub research questions in the previous chapters. The main research question reads *"How could existing condition monitoring data be used to create a new maintenance strategy for a dry bulk terminal?"*.

The maintenance strategy of the conveyor belt systems - out of all equipment on the dry bulk terminal - was chosen to be improved. This piece of equipment was chosen, because it contains the most standardized components and also covers the most surface area on the terminal. All the equipment (cranes, loaders, stacker reclaimers, etc) is connected via 27+ kilometers of conveyor belts. Additionally, the conveyor belt systems have the most condition monitoring data available. With a run-to-failure maintenance strategy for most of the conveyor belt system's components, there was room for improvement considering a condition based maintenance strategy. Finally, the malfunctions with larger failure consequences that happened during this thesis, were all taking place in the conveyor belt systems. These events are used as an example to implement and adjust the maintenance strategy.

From all the methodologies, the FMECA (Failure Modes, Effects, and Criticality Analysis) method was used to identify all potential failure modes and to create a new maintenance strategy. The FMECA is a systematic approach that gains insight in all failure modes and thoroughly investigates all their causes and effects. The failure modes can be prioritized according to their risk priority number, which is based on the failure modes' severity, occurrence and detectability. Actions are identified afterwards.

With the FMECA methodology according to ISO standard 60812 [39] a framework was put up for a new maintenance strategy to prevent extreme failure consequences. This strategy works best when kept up to date, adding data every time a new malfunction occurs and for new causes and effects. Figure 6.26 shows a flowchart the proposed maintenance strategy.

The proposed maintenance strategy starts with a malfunction. Most often, the belt is stopped automatically whenever a malfunction occurs. When this is not the case, the belt must be stopped manually. This can be done on site or via the operator in the control room. When the belt is stopped, the failure mode can be identified. This failure mode might already exist, in which case the cause and effects can be looked into in the current FMECA and the identified action(s) can be performed. When the failure mode is new (or whenever the cause or effect might be new to an existing failure mode), the FMECA must be updated. In this case it is important to save data immediately, before the data warehouse is refreshed - this happens every two weeks, because of the enormous amount of data. For new failure modes, the causes and effects must be thoroughly investigated.

If the cause can be found in the condition monitoring data and is not in line with regular operation, it is possible to implement some rules into the software. A certain threshold for a certain parameter can be added or adjusted. A combination of parameters acting in a certain way might trigger a warning. When the cause is clear and is clearly visible in data and not occurring in any normal circumstances, the threshold can be implemented in the software. If successful after some testing, the threshold might trigger a warning sign for the operator in the control room. It is also possible to implement a stop signal besides the warning. Of course, this must only be done after some testing, because unnecessary stops must be avoided.

The three case studies show that the proposed maintenance strategy works. FMECA is a promising method to analyse failure modes and to gain insight in their causes and effects. Solutions were found for the three case studies, which can be implemented in the operating software, preventing these extreme failure consequences from happening again. The proposed maintenance strategy leads to an increase in system reliability and safety, while reducing maintenance cost and unplanned downtime.

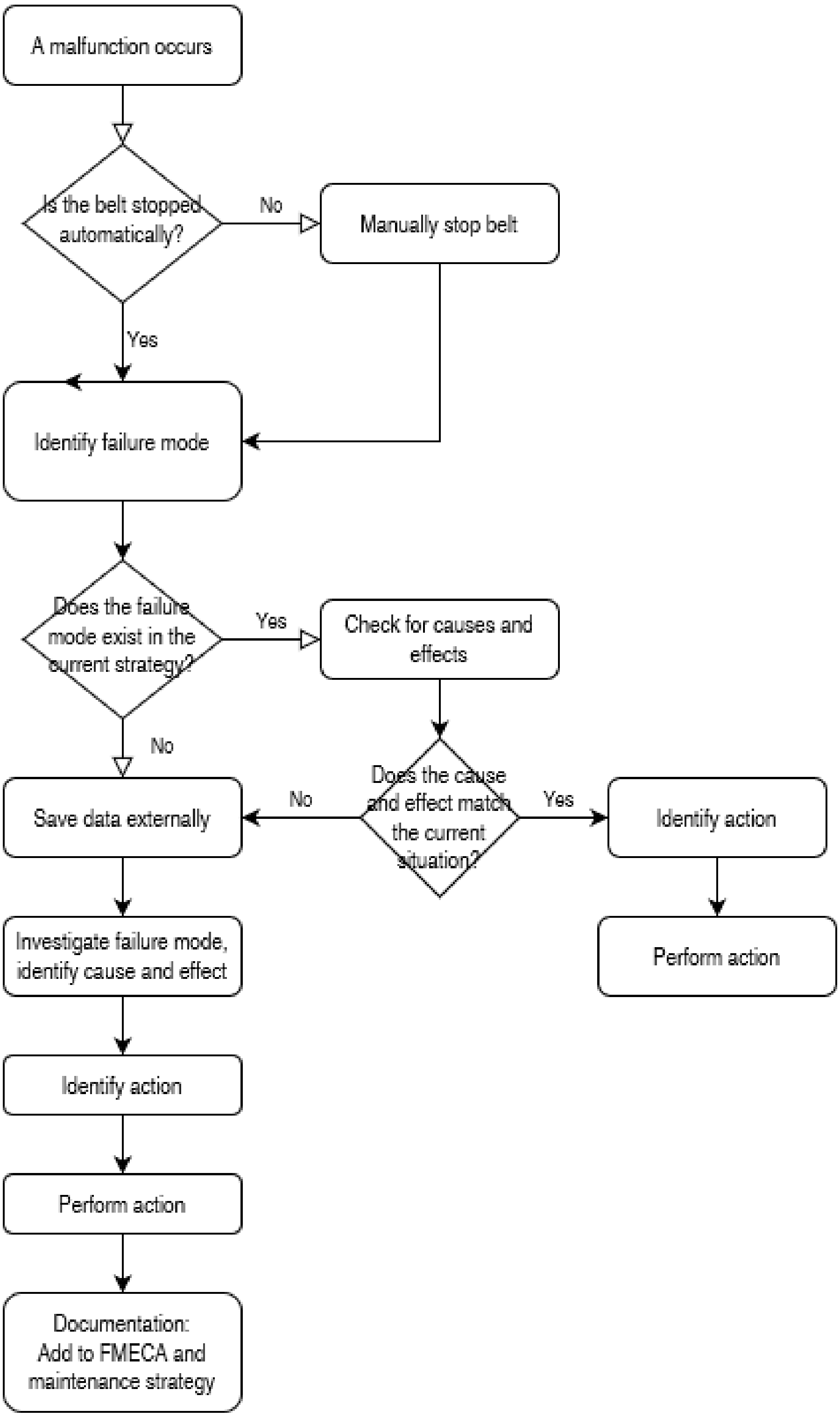


Figure 6.26: Flowchart of the new maintenance strategy with the FMECA method

Discussion

The thesis was performed at EMO B.V., where some equipment might be more advantaged than in other terminals might be. As EMO B.V. is one of the largest dry bulk terminals of Europe, numbers of throughput also can vary from other dry bulk terminals. EMO B.V. has a lot of equipment which operates fully automated, while other terminals rely on human operators more. This is why the proposed maintenance strategy might look a little different on terminals with less condition monitoring data.

Because this thesis took longer than expected, processes at EMO B.V. might have changed and improved over time. This thesis started with a lot of data from different databases of the company, which was not all clear in the beginning. Eventually, the data required for this thesis was found, but also got deleted at some points. From this was learned that the data must be saved immediately when a malfunction occurs. Unfortunately this is why there are only screenshots available of the event with belt 240, and not actual data. The screenshots are still a good representation of the data, but better understanding will be possible with actual numbers.

With better exploration of the data, there will be better understanding of early stages of malfunction. When having an operator consistently working on the malfunctions and their data, the proposed strategy can be worked out completely, creating rules for the software to stop the belt if early stages of malfunctions appear. It takes time to fully understand the data and the early stages of malfunctioning. Therefore, testing must be done. It is important to not stop the belt in unnecessary situations, like false alerts. That is why there must be one or more operators working and testing this proposal, before implementing it immediately in the software.

PowerBI has stored a lot of operational data, which can be used for better representation of the occurrence values. It is possible to indicate a chance a malfunction will happen by indicating how many times or what period of time some malfunctions took, compared to their operating time or cycles. This way, occurrence might be shown as a chance of 1 in 1000 operating hours, or a 0.001% chance within a year. With more accurate occurrence data, a more accurate priority number will be gained. This gives a more accurate priority list of failure modes as well.

The different failure modes are applicable to all the conveyor belts, but can have different values for severity, occurrence and detectability for different belts. This is because some belts are more often used than other belts, but also because some belts are more important than others. This means that it is preferred to have multiple criticality analyses executed for different types of belts. This will lead to a better fitting advice if a malfunction occurs.

The failure modes described in this thesis are not all possible malfunctions. There is always something else that could happen, that was just not thought of before or did not happen yet. Whenever a new failure mode occurs, this must be added into the strategy. The failure modes must be kept up to date and must be checked regularly to make the best of this method. The methodology works best when the failure modes are up to date, as well as their causes and effects. When new machinery is installed, this also must be taken into account with the FMECA method.

A

Scientific research paper

A maintenance strategy for conveyor belt systems in a dry bulk terminal

K.S. de Vos

Abstract

With a daily unloading capacity of 200.000 ton of dry bulk material, EMO B.V. is one of the largest dry bulk terminals of Europe. The dry bulk material is rough and the equipment handling the dry bulk must be maintained as best as possible. A specific piece of equipment will be chosen to focus this research on. With lots of condition monitoring available, but not yet optimally used, it is possible to create a new condition based maintenance strategy. Different risk assessment methods will be compared to choose the best methodology to create a new maintenance strategy. In this paper, the FMECA (Failure Modes, Effects, and Criticality Analysis) method will be proposed. This new strategy will reduce downtime and maintenance cost, while improving reliability and operation. The new strategy is tested with three case studies of malfunctions with severe consequences.

Introduction

Coal and iron ore is handled at the dry bulk terminal of EMO B.V. where it is unloaded from vessels with an average of 200.000 ton per day and transported via 75+ kilometers of conveyor belts to the storage area and other equipment. A schematic layout is shown in figure A.1, where the black lines indicate the conveyor belts and red arrows indicate the barge loaders in the Hartelhaven, quay cranes in the Mississippiehaven, train loaders (WB1-4) and stacker-reclaimers (KB1-7).

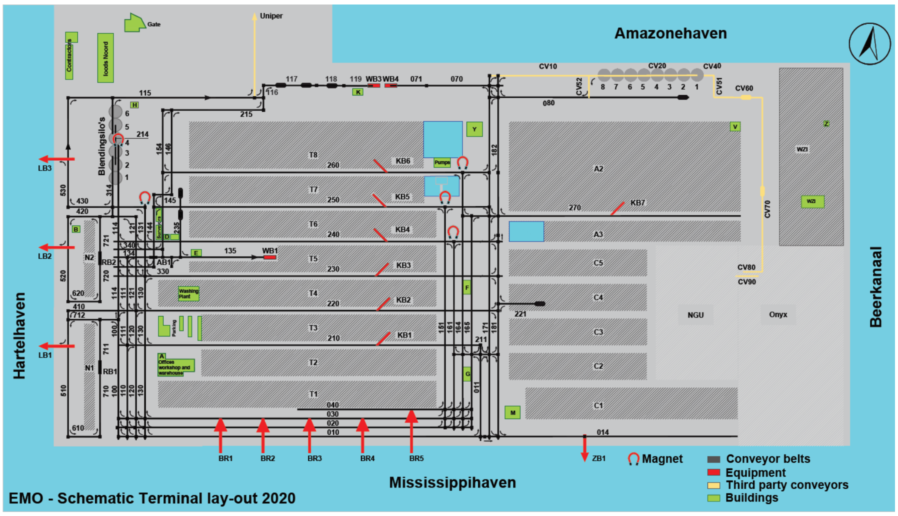


Figure A.1: Schematic lay-out of the EMO terminal 2020 (Intranet)

EMO B.V. runs according a run-to-failure and preventive maintenance strategy. A run-to-failure maintenance strategy is a suitable option for components that are smaller or have a shorter lifespan, like idlers. Lubricated components often run via a preventive maintenance strategy with regular checks, based on time, number of cycles, or operational hours. Preventive maintenance is also suitable for larger and more expensive equipment, like the belt, electromotors and gearboxes. These checks are performed regardless of the condition of the components, leading to unnecessary downtime and maintenance. This paper proposes a new solution for a maintenance strategy where downtime and maintenance cost are reduced, while increasing reliability and operation of the equipment.

Conveyor belt systems

As shown in figure A.1, the conveyor belts contain the largest surface on the terminal, connecting all the equipment together. The conveyor belts consist of several components, shows in figure A.2 and addressed in table A.1. Most conveyor belts at EMO B.V. operate in two directions and have a constant operational speed of 4.5 m/s. The belt is made of rubber and reinforced with steel. In total, the terminal has installed a couple hundred thousand idlers to carry the more than 75 kilometers of conveyor belt and its dry bulk material.

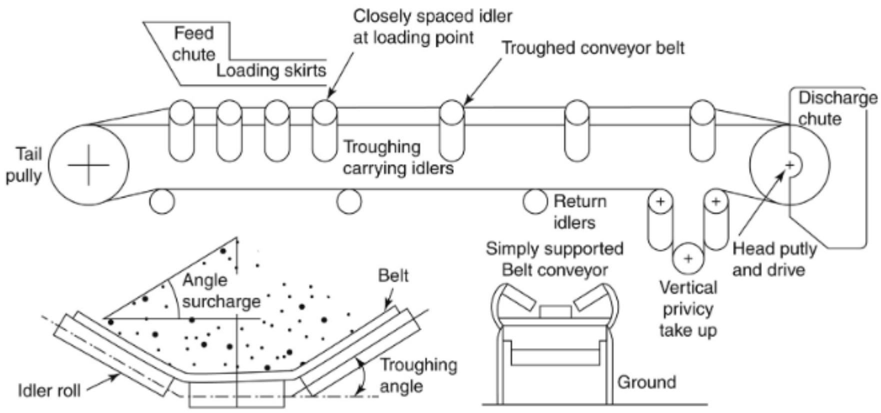


Figure A.2: A schematic overview of a conveyor belt system [19]

Component	Function
Idlers	Supporting the conveyor belt, prevent sagging, guiding the conveyor belt
Conveyor belt	Carrying the bulk material from one point to another
Electromotor	Deliver torque to drive the conveyor belt
Gearbox	
Pulleys	Supporting the conveyor belt when it changes direction
Tensioning device	Maintaining proper tension in the belt
Structure/ frame	Support the entire conveyor belt system

Table A.1: Functions of different components of the conveyor belt system

After researching the existing condition monitoring data of EMO B.V. and performing a literature study of researching patents, international standards, and journals about condition monitoring and maintenance solutions in a dry bulk terminal, concludes was to create a new maintenance strategy for the conveyor belt systems.

Research methodology and analysis

To create a new maintenance strategy, some criteria is set up. The most important criterion is that the new maintenance strategy must be based on existing condition monitoring data. All malfunctions must be included, as well as their causes and consequences (effects). The strategy must be flexible enough to adjust or add malfunctions with their respective causes and effects. A criticality analysis or risk assessment must be possible and eventually the strategy must contribute to a reduce in downtime and maintenance cost, which leads to improved reliability and operation. To provide to the state-of-the-art and keep the company at the top of the dry bulk terminals, the strategy must be easily adjustable to other equipment or other terminals. It helps when the strategy is based on a worldwide acceptable standard, like ISO. Table A.2 summarizes these criteria with the different risk assessment methods to create the new maintenance strategy.

Criteria	FTA	ETA	PRA	HAZOP	FMEA	FMECA
Existing data	v	v	v	-	v	v
Causes	v	-	v	-	v	v
Effects	-	v	v	v	v	v
Criticality	-	-	v	v	-	v
Downtime -	v	v	v	-	v	v
Cost -	v	v	v	-	v	v
Reliability +	v	v	v	-	v	v
Applicability	v	-	-	v	v	v
Main focus	Cause	Effect	Risk	Safety	Failure	Failure

Table A.2: Criteria per methodology; Fault tree analysis, event tree analysis, probabilistic risk assessment, hazard and operability analysis, failure modes and effects analysis, and failure modes, effects and criticality analysis

FMECA methodology

As shown in table A.2, the FMECA methodology is proven to be the best suitable methodology to create the new maintenance strategy. This strategy is created according to the international standard 60812 [39], as shown in the flowchart in figure A.3 and summarized in the following steps:

- Step 1: Define system, define boundaries (table A.1)
- Step 2: Identify failure modes (table A.5)
- Step 3: Identify effects
- Step 4: Identify causes
- Step 5: Determine risk priority numbers (tables A.4 and A.3)
- Step 6: Identify actions

As **step 1** is already described in the first part in table A.1, **step 2** will be summarized in table A.5. For **step 3** (identify effects) and **step 4** (identify causes), the previous table will be expanded exponentially. In this report a brief example is shown with their respectibe risk priority numbers and actions (**step 6**) in table A.6.

To be able to prioritize the different failure modes, a criticality analysis (**step 5**) must be performed. According to the FMECA methodology, a risk priority number must be calculated, where the values for detectability, occurrence and severity are multiplied by each other. These values are based on a 1 to 10 scale, resulting in a risk priority number between 1 and 1000 [39] [24] [71] [65].

Rating	Severity	Detailed description
1	Very minor	System is fully operational, no effect on system performance, not noticed by operator, no safety issues, no financial losses
2	Minor	System is fully operational, no safety issues, operation with minor side effects (i.e. noise), unlikely to be noticed
3	Very low	System is fully operational, insignificant physical damage, side effects (i.e. noise, vibrations), weak impact
4	Low	System is fully operational, minor physical damage, operation is accompanied by side effects, negligible impact
5	Moderate	Discernible influence
6	Moderately high	Considerable influence
7	High	Major impact
8	Very high	Acceptable impact
9	Critical	Very serious impact
10	Catastrophic	

Table A.3: Severity ratings [65]

Rating	Detection	Rating	Occurrence
1	Almost certain	1	Almost never
2	Very high/ very likely	2	Individual cases
3	High/ likely	3	Very rarely
4	Moderately high	4	Rarely
5	Moderate	5	Low probability
6	Low	6	Average
7	Very low	7	Quite high
8	Remote/ unlikely	8	High
9	Very remote/ very unlikely	9	Very high
10	Almost uncertain/ almost impossible	10	Almost always

Table A.4: Rating scale for detectability and occurrence [65]

Component	Failure mode	Component	Failure mode
Idlers	Bearing failure	**Gearboxes**	Oil leak
	Overheating bearing		Gear wear
	Damaged bearing		Breakage of gear tooth
	Misalignment in rollers		Overheating
	Damaged idlers/ rollers		Misalignment
	Blocked rollers		Vibration
			Housing damage
Conveyor belt	Wear		Gear tooth damage
	Belt tracking		Backlash change
	Damaged rubber belt		
	Tear in rubber	**Pulleys**	Bearing failure
	Splice issues		Misalignment
	Steel cords damage		Wear
	Steel cords breakage		Material buildup
	Slipping belt		Slipping belt
	Emergency line pulled		Blocked pulley
	Melted rubber		
	Tensioning problems	**Tensioning device**	Bearing failure
			Misalignment
Electromotors	Failing to start		Over tensioning
	Misalignment of shaft		Under tensioning
	Bearing failure		Failing to start
	Overheating		Counterweight failure
	Winding insulation failure		Wear
	Rotor/ stator failure		Hydraulic/ pneumatic issues
	Vibration		
	Contamination	**Structure/ frame**	Cracks
	Oil leak		Tear
			Breakage

Table A.5: Several failure modes per component [16]

New maintenance strategy

A proposal for new maintenance strategy is shown in figure A.4. This flowchart is a simplified overview of the maintenance strategy. Eventually, the maintenance strategy will contain a large database with data of malfunctions and algorithms to prevent the same malfunctions from happening. Every malfunction must be investigated and if possible, an algorithm will recognize the irregularities in the condition monitoring data and warn if early signs of failure occur. This way, the strategy is able to prevent larger

Failure in belt	Effects	Causes	RPN	Actions
Dent	Tear	Heavy load	36	Continue operation
Tear	Larger tear or splice	Sharp piece in load	12-160	Repair if possible
Loose cord	Damage belt or idlers Dangerous	Wear, damaged belt	18-72	Stop operation; remove cord
Belt tracking	Onesided wear, Uneven load on belt and idlers (leading to uneven wear)	Uneven load distribution, Belt placement	9-27	Continue operation; Check load distribution and belt placement

Table A.6: Step 3, 4 and 6 for the FMECA methodology: identifying effects, causes, and actions. Shown with the respective risk priority numbers

failure consequences and a decision can be made about maintaining the equipment or continue or adjust operation.

Case studies

During this research, some malfunctions occurred with large failure consequences. From these events is learned that data must be saved and stored immediately after a failure has occurred. As there is a lot of condition monitoring data available, the data warehouse is renewed every week or two. Therefore, when a malfunction occurs, data must be saved externally to prevent it from being deleted after two weeks. This data will then be investigated and if it was possible to prevent larger consequences, this will be added as a warning in the condition monitoring software.

For example, in belt 030 the axle of the gearbox broke. This was traceable in the data for multiple parameters, ruling out a faulty sensor. The torque of one drive unit drops to 0, where the other becomes twice as high to compensate for the broken drive unit. Another indication is that the winch pressure suddenly goes up. The power of the broken down drive unit drops to zero as well and the rpm of the second drive unit goes up. These are all indicators that some part of the drive unit has broken down. Eventually, these rules can be implemented in the software and create a warning, while the belt will be stopped automatically. This to prevent larger damage, where for example gears can break or loose teeth.

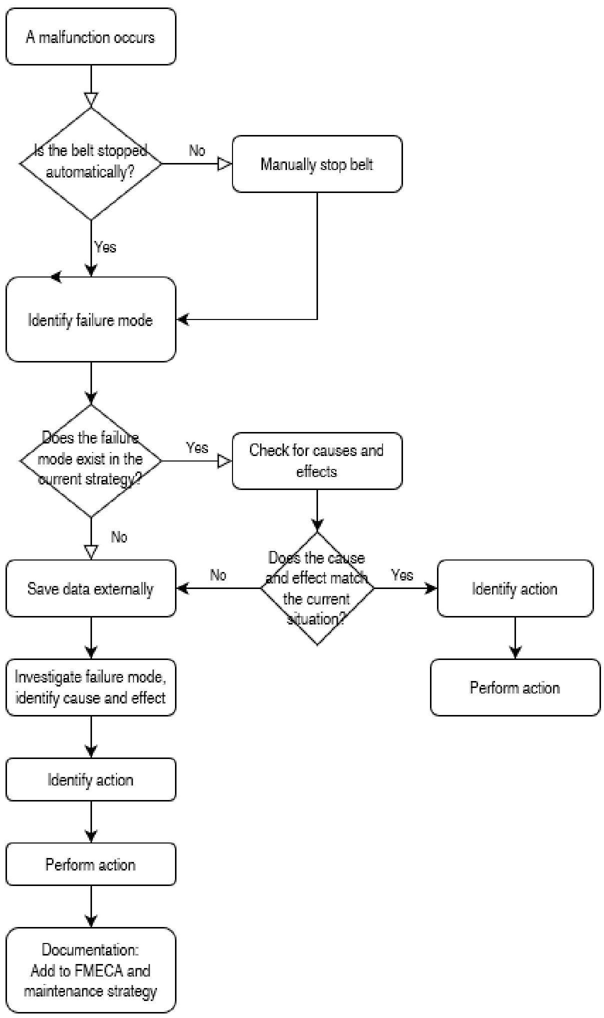


Figure A.4: Flowchart of the new maintenance strategy with the FMECA method

Conclusion

The FMECA methodology was used to create a new maintenance strategy for conveyor belt systems in a dry bulk terminal. All possible malfunctions are thoroughly investigated as well as their causes and effects. By criticality analysis, the different malfunctions can be prioritized. The proposed maintenance strategy works well for three case studies and is applicable to other equipment and terminals. This is a state-of-the-art solution, as no dry bulk terminal makes use of this methodology yet. Only few research papers were found on performing a FMECA methodology in dry bulk terminals.

Discussion and future remarks

Some data was lost during this thesis. Therefore, the rule was implemented to immediately save all data available whenever a malfunction occurs. The risk priority numbers might not be completely reliable as occurrence numbers can be determined based on actual operating numbers, using the data from PowerBI. This will be a great improvement of the maintenance strategy.

Acknowledgement

This research is performed for the Multi Machine Engineering department of the Technical University of Delft in collaboration with the dry bulk terminal of EMO B.V.

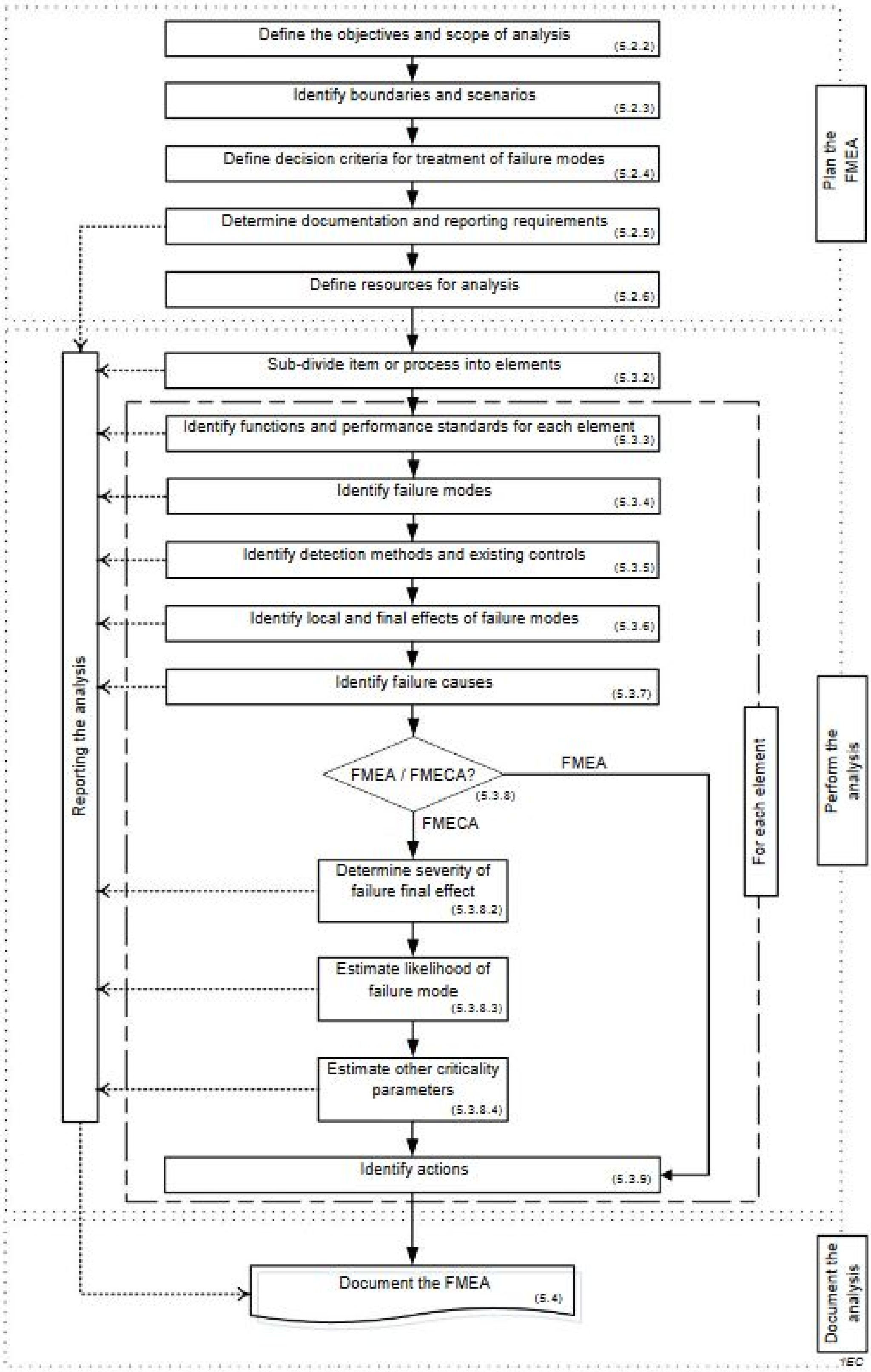


Figure A.3: Overview of FMEA methodology before tailoring according to international standard IEC60812 [39]

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B
Graphs of the Overall Equipment Effectiveness at EMO B.V.

OEE per equipment

Cranes

Figure B.1 shows the overall equipment efficiency of the 50 tonnes cranes over the past 5 years. Note that BR1 is currently shut down and therefore has no operational hours since November (19) 2020.

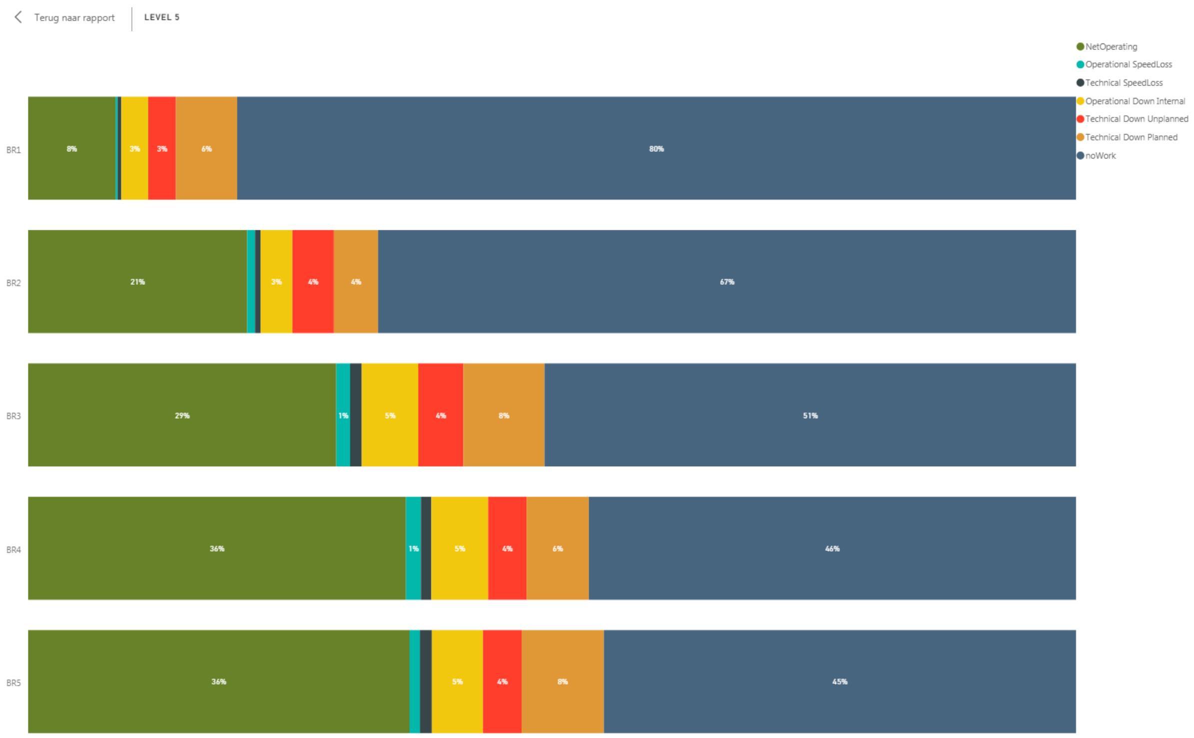

Figure B.1: Overall equipment efficiency of the past 5 years of the cranes at EMO B.V. (11 Jan 2022)

Barge loaders

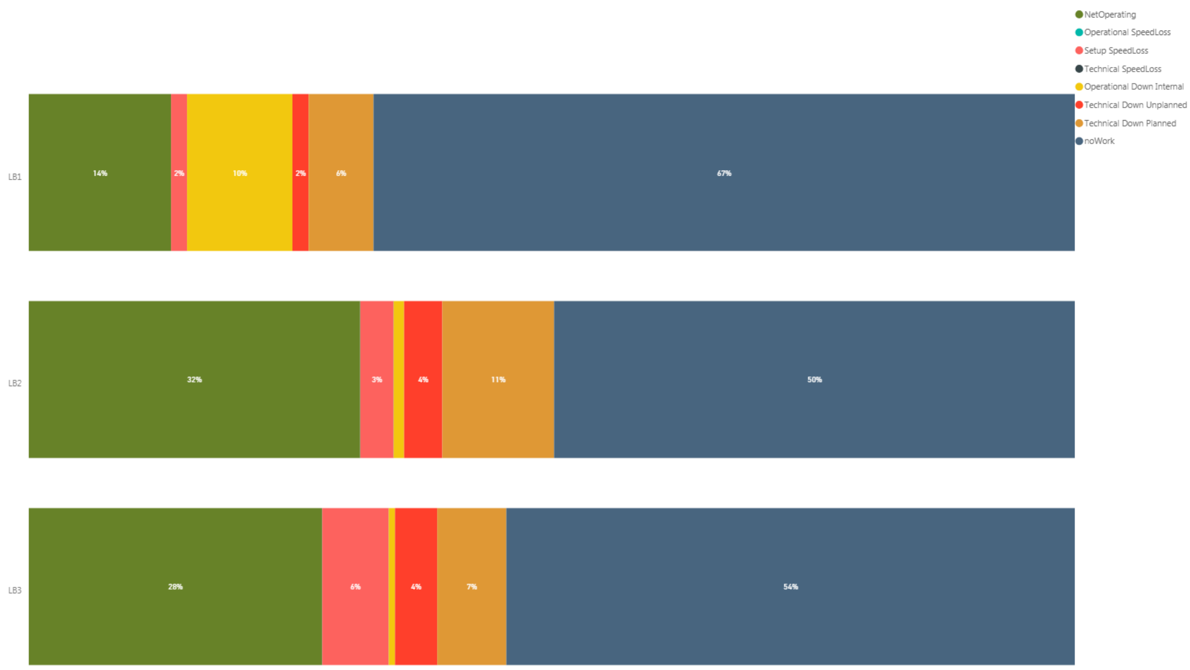

Figure B.2: Overall equipment efficiency of the past 5 years of the barge loaders at EMO B.V. (11 Jan 2022)

Stacker reclaimers

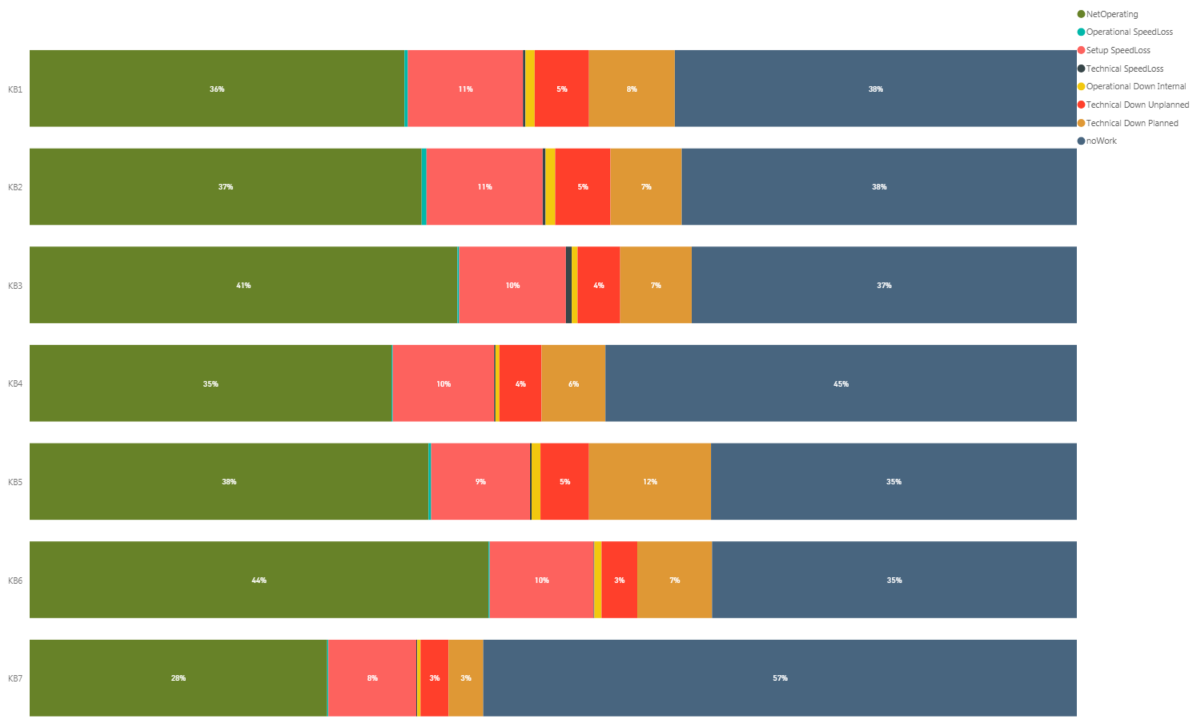

Figure B.3: Overall equipment efficiency of the past 5 years of the stacker reclaimers at EMO B.V. (11 Jan 2022)

Conveyor belts

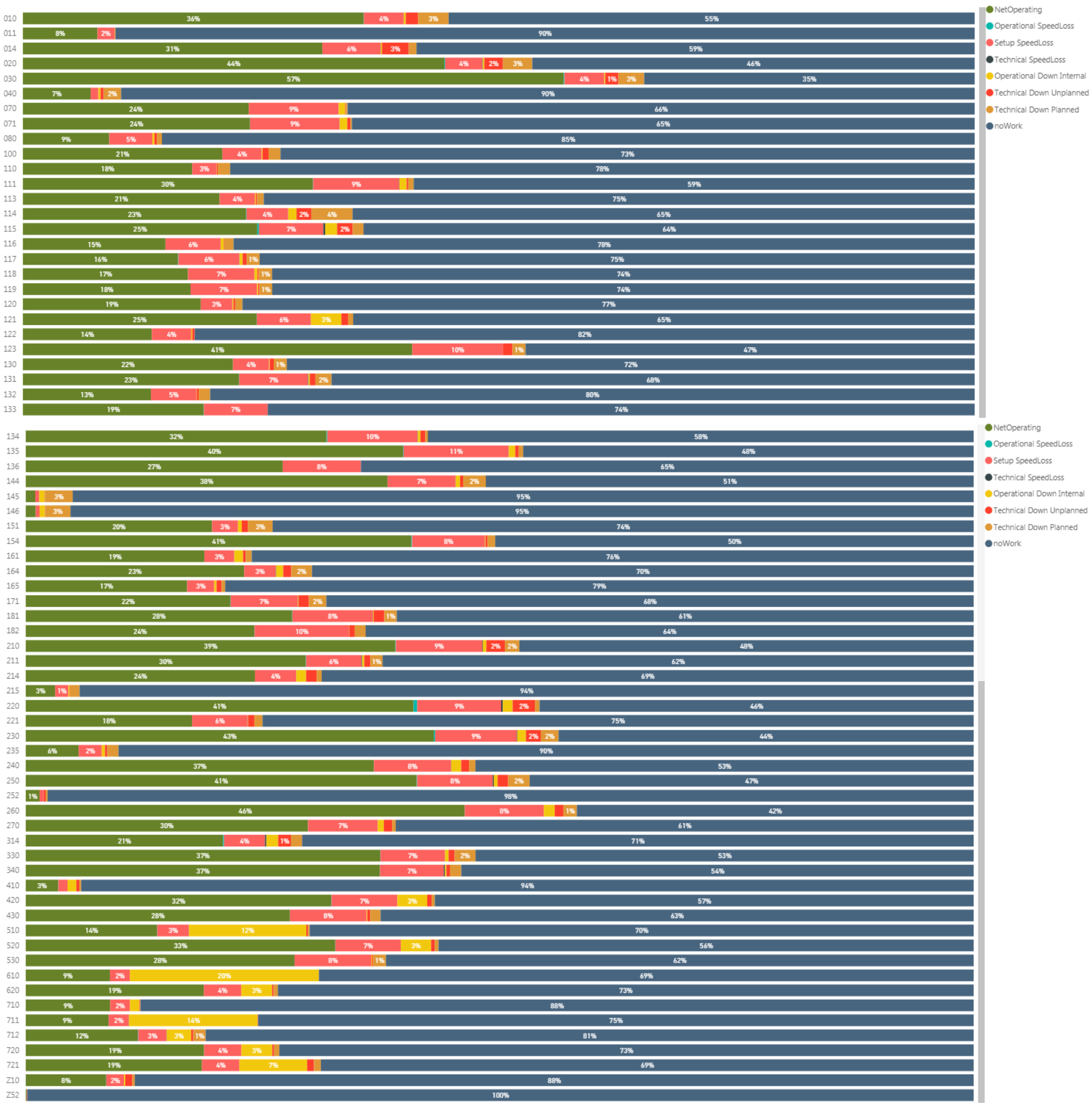

Figure B.4: Overall equipment efficiency of the past 5 years of the conveyor belts at EMO B.V. (11 Jan 2022)

Train loaders

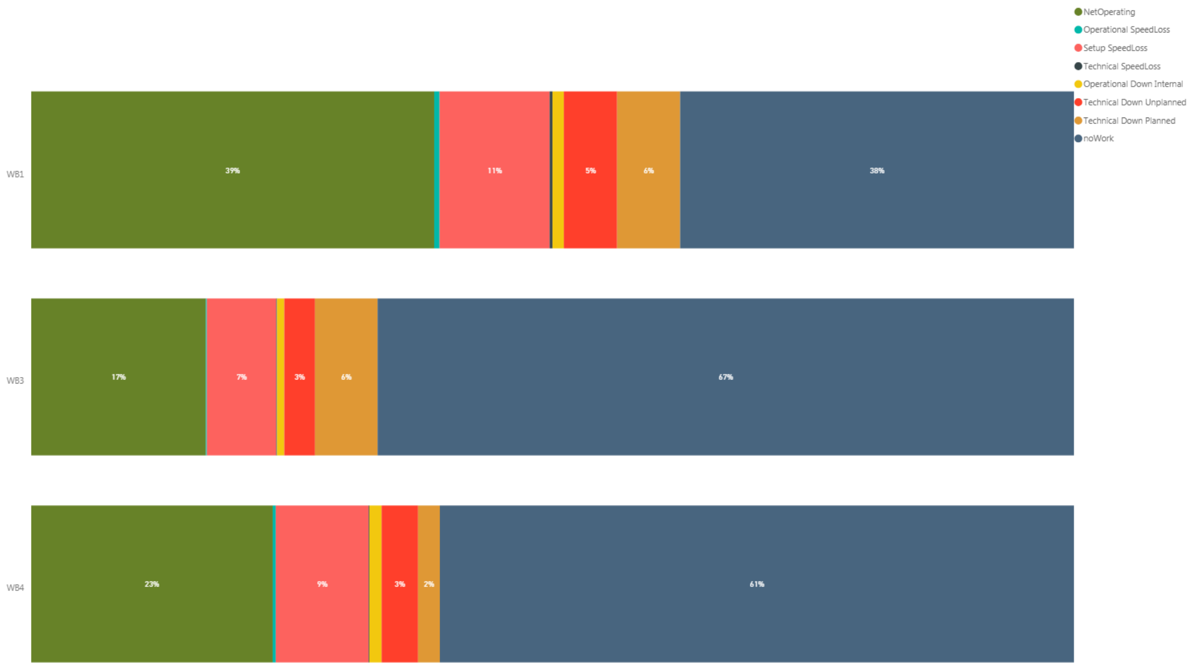

Figure B.5: Overall equipment efficiency of the past 5 years of the train loaders at EMO B.V. (11 Jan 2022)

C

Logs on three case studies

This appendix contains the logs on the three case studies in Dutch. These logs are a direct copy from EAM [16].

Belt 171

31-01-2022:PK/DG: Een oplettende laadschoprijder zag rookontwikkeling uit de tunnel komen. Direct alarm geslagen, ter plekke gelijk de brand gaan blussen in samenwerking met reeds gearriveerde bedrijfsbrandweer. Waterwagen van HSR was ook ter plekke en heeft op de bovenkant van de tunnel geblust. Toen de gezamenlijke brandweer (deze was inmiddels al opgeroepen iv.m. mogelijke uitbreiding) arriveerde was de brand al meester.

Oorzaak blijkt een onderrol die uit zijn lager is gelopen en na schoondraaien is band stilgezet, door de warmte ontwikkeling is de band in brand gevlogen. Schade is dat ruim 4 meter van het onderpart vervangen moet worden en de onderkant van het bovenpart heeft ook brandschade. Weging en bekabeling heeft ook brandschade. Constructie lijkt niet beschadigd. *Aangemaakt: 31-JAN-2022 22:00; P.D. Kloet (KLOPIE)*

BvdH/MvdZ: Rondom bekabeling welke verbrand is afzetlint geplaatst. Aan Westkant in kabelgoot ligt een Pvc-pijp, waarin zich waarschijnlijk een glasvezel kabel bevind. Pijp is enigszins gesmolten, glasvezelkabel lijkt het overleefd te hebben. *Aangemaakt: 01-FEB-2022 02:31; B.van de Hout (HOUBEN)*

01-02 GM: mild aangetaste groene glasvezelbuis verzorgt met twee minikabels in dukts de verbinding van st.Y naar Onyx. Naar het Emragebouw met 24x singlemode, allen niet in gebruik en een kabel 6x singlemode naar top v/d de silo's. Deze zijn voor het camerasysteem Gem.Havenbedrijf , waar men geen storing heeft. Zie foto's. Wat geheel verast is betreft de kabeltjes van de loadcellen bandweging en de kabel naar de junctionbox. *Aangemaakt: 01-FEB-2022 15:00; G.J. Mijnlieff (MIJGER) Gewijzigd: 01-FEB-2022 15:03; G.J. Mijnlieff (MIJGER)*

Band 171 goed gezet voor het plaatsen van een passtuk van 146 meter.We gaan morgen het een en ander voorbereiden.Donderdag komt Narviflex voor het maken van twee verbindingen. *Aangemaakt: 01-FEB-2022 15:31; R. Willemstein (WILROB)*

Vandaag aan zuid zijde band doorgeslepen en afgespannen . Aan noord zijde stelling laten Bouwen voor toegang te verkrijgen tot band 171. Ook hier de band afgespannen.de hampelman is met een 450 tons kraan van peineman gelift.en hangt nu in kettingen. Morgen ochtend gaan we de band eruit trekken (oud aan nieuw). *Aangemaakt: 02-FEB-2022 15:43; R.D. Donkers (DONROB)*

Vandaag passtuk erin getrokken (is 151 meter geworden).2x onder traverse opgebouwd en de tenten geplaatst. Naviflex is begonnen met het strippen van de band. morgen verder met strippen dicht leggen van de band en dan gaan we bakken. *Aangemaakt: 03-FEB-2022 17:03; R.D. Donkers (DONROB)*

04-2-22 Jvdw/HT loadcellen uitgewisseld voor 1500 pond load cellen de bestaande kabel had nog genoeg lengte erin om bij de junctie box te komen het geheel weer aangesloten en in station Y gekeken op de siwarex of alles goed stond bij PMB geweest om de schalering aan te passen van 1000pond naar 1500pond zaterdag met inbedrijfstellen moet de rest nog getest worden. *Aangemaakt: 04-FEB-2022 15:45; Harm Tramper (TRAHAR)*

Het strippen van de oude band aan noord zijde zit erg tegen . De planning is om rond de klok van 17:00 de boven traverse aan zuid zijde te plaatsen. En rond de klok van 18:00 aan noord zijde de boven traverse te plaatsen.De planning is om vanavond allebij de verbindingen te bakken.Morgen ochtend afbreken. *Aangemaakt: 04-FEB-2022 16:07; R. Willemstein (WILROB)*

VOOJOH: Verbindingen afgebroken rollenbokken terug geplaatst rollen gecontroleerd, hampelman laten zaken opgeruimd. Band terug geven aan TD spil... *Aangemaakt: 05-FEB-2022 14:20; R. van Rossen (ROSRIC)*

Spil4: Tijdens testen van de band bleek er nog een steun t.b.v. rollensteun bovenpart op de band te liggen. Met draairichting Noord is steun naar noodlager 4 gedraaid. Hierna Stuurplaat Noord en verscheidene langs geleidingen van de band gecontroleerd op eventuele schade. Draairichting Noord 2 onderollen gesteld aan de Zuid, betreft de 1ste 2 2delige onderollen. De rollen stonden sturend, staan nu weer recht. Draairichting Zuid geen problemen ondervonden. Na +/- 45 minuten draaien band weer terug gegeven aan productie. *Aangemaakt: 05-FEB-2022 18:50; K. Tiben (TIBKEV)*

Belt 240

SP3; Band 240 was stil gevallen met een scheefloop. Bandenman constateerde hierbij een lengtescheur in de band. De band nagelopen en de scheur loopt van onderpart 310 meter t/m bovenpart 1065 meter en van bovenpart 1000 meter tot bovenpart 915 meter. Met de hele ploeg de band op en af gelopen, maar nog geen oorzaak kunnen vinden. ME ingelicht. *Aangemaakt: 10-FEB-2022 05:24; T.M. SCHOLTS (SCHTON)*

Schade opgenomen lengte scheur loop van midden bandstuk 6644 naar einde van bandstuk 5377. Lengte schade is 1600meter band welke vervangen moet worden . Morgen schoondraaien van de band. *Aangemaakt: 10-FEB-2022 15:52; R. Willemstein (WILROB)*

Lading welke nog op band lag is er vanaf gedraaid. *Aangemaakt: 11-FEB-2022 15:07; R. Willemstein (WILROB)*

Maandag 14-2 aanvang reparatie. Zekeringen en 240 en KB4 zijn getrokken. Bandsnelheid 240 staat nog op 25% ingesteld. *Aangemaakt: 11-FEB-2022 16:38; G. Volmer (VOLGEE) Gewijzigd: 11-FEB-2022 16:52; G. Volmer (VOLGEE)*

Vandaag het een en ander voorbereid voor het vervangen van de band. Haspelstation banden (800 meter en 720 meter) vervoerd naar terrein 5.De 800 meter cassette in haspelstation geplaatst. En de wangen geplaatst .Morgen ochtend de band overhaspelen. Er is voor morgen een 450 Tons kraan besteld om de band te verplaatsen richting band 240. *Aangemaakt: 14-FEB-2022 19:02; R.D. Donkers (DONROB)*

Vandaag als eerste het haspelstation geplaatst in de constructie van band 240.Daarna de 800 meter rol geplaatst in het haspelstation. Deze combinatie te samen is te zwaar voor de hijs ogen die zijn geplaatst op het haspelstation.(totaal is dit 60 ton).De 800 meter band hebben we er met behulp van een laadschop (ML14) er in getrokken. De tent aan west zijde is opgebouwd. *Aangemaakt: 15-FEB-2022 16:37; R.D. Donkers (DONROB)*

Vandaag 400 meter in het haspelstation geplaatst en naar de nieuwe 800 band getrokken (moet nog wel verder worden ingetrokken) . Met heel veel pijn en moeite de pers opgebouwd in de oost.(te veel wind).Narviflex is in de west begonnen met het strippen van de band. De weersverwachting voor komende dagen voorspellen niet veel goeds .Dit gaat waarschijnlijk de werkzaamheden wel beïnvloeden. *Aangemaakt: 16-FEB-2022 15:56; R.D. Donkers (DONROB)*

Vandaag in de west begonnen om de band dicht te leggen en te bakken .Morgen ochtend wordt deze afgebroken. Aan oost zijde vanmorgen begonnen met het strippen en dicht leggen van de band . misschien vanavond nog bakken en anders morgen ochtend vroeg. morgen ochtend voor 10:00 willen we de boven traverse zowel in de oost en de west al gaan afbreken (met de hand) in verband met de slechte weersomstandigheden (veel wind) we zullen moeten wachten op beter weer om de tent en de onder traverse af te kunnen breken om de band er verder in te trekken en het laatste stuk band er in te trekken.(360 meter). *Aangemaakt: 17-FEB-2022 20:20; R.D. Donkers (DONROB)*

Vandaag de verbinding aan oost zijde gebakken. aan west zijde hebben we de boven traverse af gebroken en opgeruimd we kijken hoe de weersomstandigheden zich ontwikkelen om de werkzaamheden weer te kunnen hervatten. wegens de weersomstandigheden verlaten wij het emo terrein rond de klok van 13:00 Narviflex heeft het terrein verlaten rond de klok van 11:00. *Aangemaakt: 18-FEB-2022 12:43; R.D. Donkers (DONROB)*

Vulcanisatie tenten zijn er af gehaald en ondertraverse verwijderd ,verder gegaan met intrekken 400m rol en een gedeelte van rol 365m . Gaan morgen restant van rol intrekken. *Aangemaakt: 22-FEB-2022 19:56; R. Willemstein (WILROB)*

Restant van rol ingetrokken ,stukken band bij elkaar getrokken zodat verbinding gemaakt kan worden . Onder pers opgebouwd bij verbinding in de oost ,hier kan begonnen worden met strippen van de band . *Aangemaakt: 23-FEB-2022 19:36; R. Willemstein (WILROB)*

Vandaag de rest van de vulkanisatie spullen opgebouwd. vanavond wordt de verbinding in de oost gebakken. de verbinding in de west wordt vanavond nog dichtgelegd en morgen ochtend gebakken. het haspelstation is ook uit de constructie getild . morgen gaan we beginnen met alles terug te bouwen en de tenten af te breken. *Aangemaakt: 24-FEB-2022 17:01; R.D. Donkers (DONROB)*

Maandag wordt de waterleiding hersteld. Gereed. *Aangemaakt: 25-FEB-2022 15:25; R. Bekker (ME) (BEKROB) Gewijzigd: 28-FEB-2022 15:30; R. Bekker (ME) (BEKROB)*

Vulkanisatie van de laatste 2 verbindingen is afgerond ,spullen opgeruimd . Constructie bandstraat is weer sluitend gemaakt . Haspelstation moet nog wel weg gehaald worden van de kombi baan in de oost, en nog rubber van rubber van terrein 6 met laadschop wegtrekken .Band is opgespannen en proefgedraaid oost en west ziet er goed uit. *Aangemaakt: 25-FEB-2022 20:02; R. Willemstein (WILROB)*

Vandaag het haspelstation verplaatst naar de gasunie Morgen gaan we het restant oude band (600 meter) opruimen. *Aangemaakt: 01-MRT-2022 15:46; R.D. Donkers (DONROB)*

Oude band opgeruimd. Werkzaamheden band 240 vandaag afgerond. Werk gereed. *Aangemaakt: 02-MRT-2022 16:07; R.D. Donkers (DONROB)*

Belt 030

22-07 spil1: 030 aandrijving oostkant oost lag koppeling tussen de motor en de tandwielkast eruit. Toen keuze gemaakt om te kijken of we met 3 aandrijvingen konden verder gaan. kap over verloop van TWK naar trommel maakte schurend geluid. besloten om band leeg te draaien en alles stil te zetten. na 4 min brak as tussen twk en trommel. Alle zekeringen getrokken voorlopig. *Aangemaakt: 22-JUL-2022 04:32; J. Kerkmans (KERJOH)*

BvdH: Met inspectie en MW de boel beoordeeld, 2 koppelingen defect, trommel iets opgeschoven. Band leeggedraaid. MWDD gaat nu eea borgen zodat band met 3 aandrijvingen terug komt. Terugplaatsen 4e drive laat nog tijdje op zich wachten. Keuzeschakelaar in station staat op aandrijving 3 (Oost/West). Let wel, er zitten sommige coderingen verdraaid in de staart!!! Hier is Arjan K. nu mee bezig. Let ook op beperkt tonnage eerste tijd. *Aangemaakt: 22-JUL-2022 14:04; B.van de Hout (HOUBEN); Gewijzigd: 22-JUL-2022 14:13; B.van de Hout (HOUBEN)*

MW: Heeft de koppeling aan de as geborgd met 3 lassen zodoende kan de koppeling niet meer van de as afschuiven. De TWK is geborgd naar het zuiden dat de TWK niet tegen de koppeling aanstaat. *Aangemaakt: 22-JUL-2022 14:55; M. GREVENBROEK (GREMIK)*

Als de band weer gaat draaien graag de eerste tijd lagers van de aandrijftrommel controleren. *Aangemaakt: 22-JUL-2022 15:58; J.G. van der Leer (ME) (LEEJOS)*

De verdraaide meldingen, ingangen en uitgangen van aandrijving 3 en 4 in orde gemaakt. De zekeringen van aandrijving 4 zijn nu getrokken en er kan nu met PM030 gedraaid worden. Tonnage blijft beperkt tot 2200ton/uur draaiend naar de oost en 2500ton/u naar de west. *Aangemaakt: 22-JUL-2022 17:12; A. Keijzer (KEIARJ); Gewijzigd: 22-JUL-2022 18:21; J.G. van der Leer (ME) (LEEJOS)*

23/07 EdG: Start richting de oost. LW op de hoogte gesteld van tonnagebeperking (ca 2000/2200t/h). Trommel en lagers lopen rustig. Na 4 uur nogmaals blik geworpen, trommel en lagers draaien nog steeds rustig. Tevens nog een Flir meting gedaan op beide lagers van de"voormalige" aandrijftrommel. Beide ca 28 graden. *Aangemaakt: 23-JUL-2022 08:52; E. de Goeij (GOEIED); Gewijzigd: 23-JUL-2022 12:26; E. de Goeij (GOEIED)*

BvdH: Band heeft hele dienst gedraaid. Loopt netjes, lagers blijven dezelfde temp en draaien zonder bijgeluiden. *Aangemaakt: 23-JUL-2022 22:24; B.van de Hout (HOUBEN)*

24/07 EdG: Controle uitgevoerd, geen veranderingen. Temperatuur lagers is iets gestegen naar 31.5 graden. *Aangemaakt: 24-JUL-2022 11:11; E. de Goeij (GOEIED)*

25/07 EdG: Lagers en trommel gecontroleerd. Geen veranderingen. *Aangemaakt: 25-JUL-2022 19:04; E. de Goeij (GOEIED)*

D

Traces of belt 240

This appendix shows some of the most important traces found on belt 240 after this belt was spliced in half over a length of 1600 meters. As can be seen in the traces, the belt was started and stopped several times before it spliced. During operation the belt runs at a constant speed of 4.5 m/s, which means that it takes around 355 seconds (almost six minutes) to damage the belt over a length of 1600 meters.

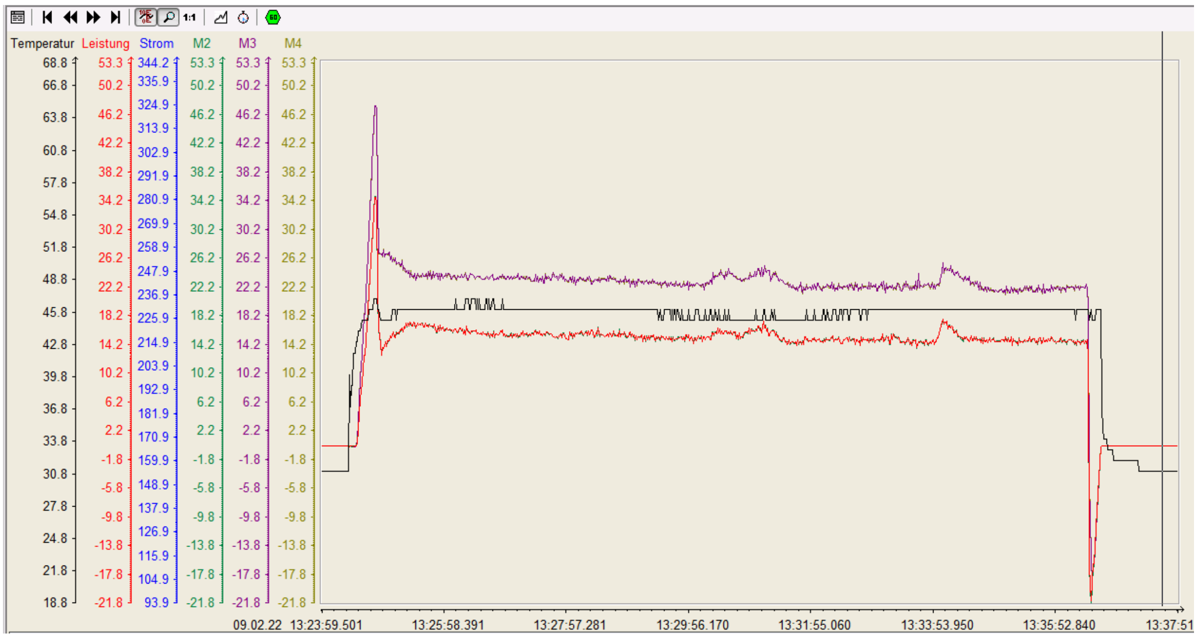

Figure D.1: Regular start-up and stopping of a conveyor belt system. Traces are from belt 240 on 9 February 2022

Figure D.1 shows a regular starting up and stopping of the conveyor belt system of belt 240. The pictures in figure D.2 show multiple operations of belt 240 on 9 February and 10 February 2022. After 11:40 the belt switches direction as can be seen in the change in power output values. After a while the power output values start scattering. This scattering increases over time. The bottom picture shows a close-up of the top picture.

Figure D.2: Operation of belt 240 on the day of the event (10 February 2022). As can be seen there is an increase in scattering and values of power output of all drive units

The following figures contain close-ups of the traces, respectively in time according to the figure captions.

Figure D.3: Close-up of the power output between 0:28 and 2:59 and a close-up between 0:28 and 2:15

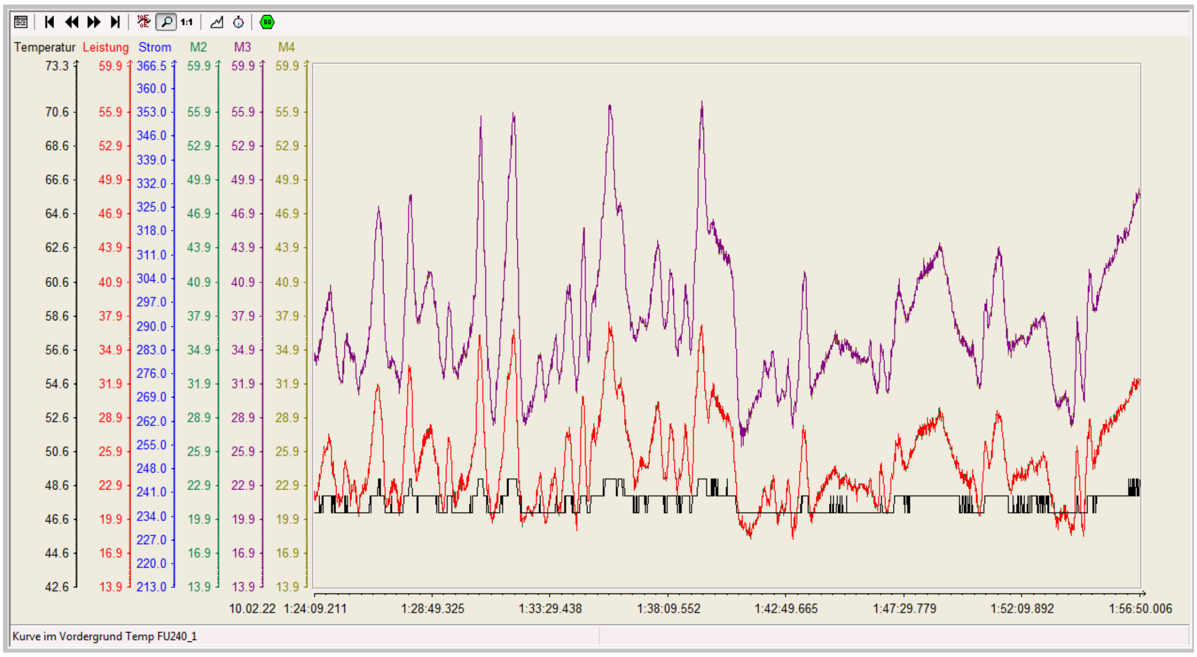

Figure D.4: Zooming in between 1:24 and 1:56 to show the amount of scattering

Figure D.5: Close-up between 2:27 and 2:53

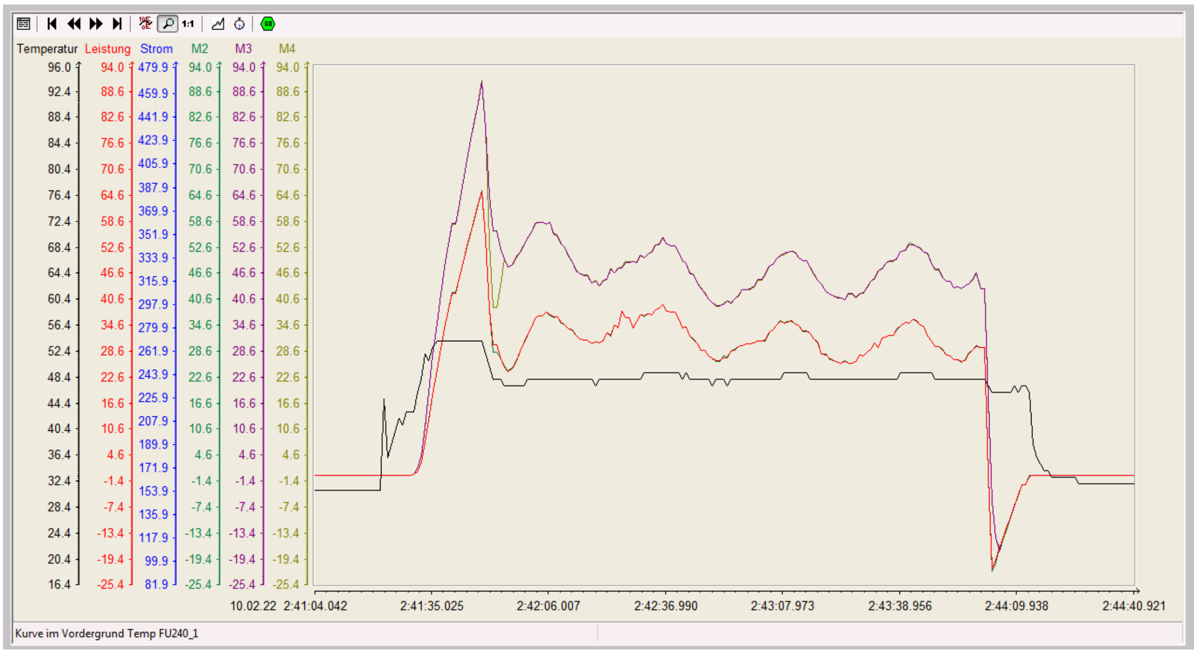

Figure D.6: Close-up 2:41 to 2:44

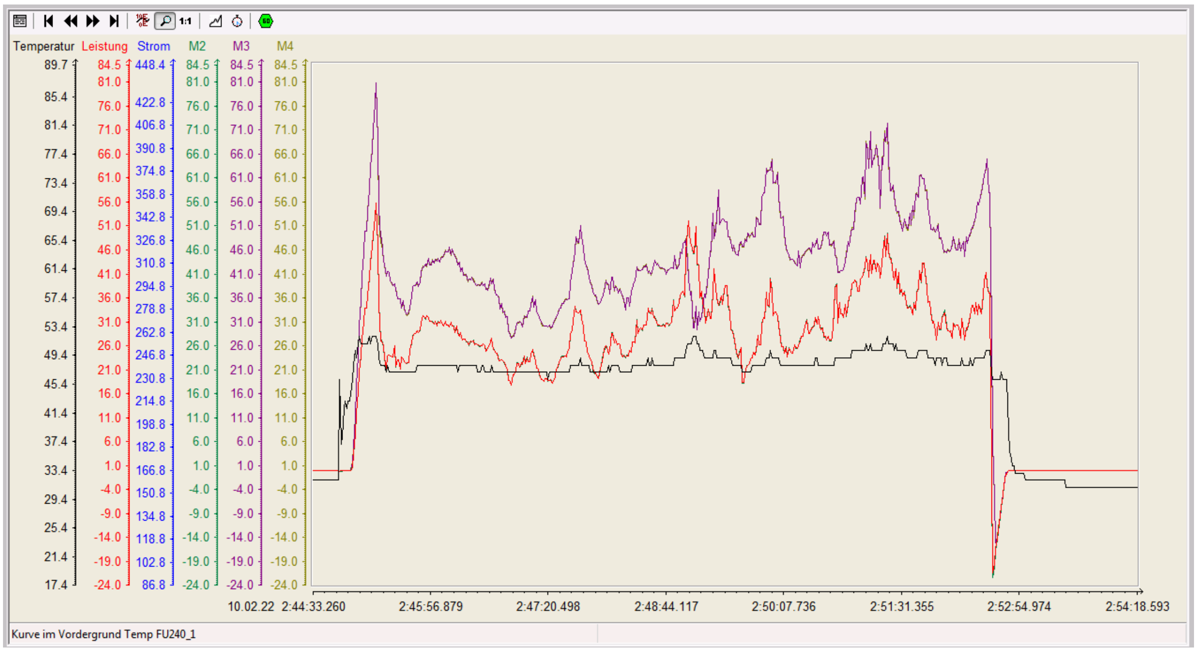

Figure D.7: Close-up of the part where the drive units switch in power output values

E

Literature studies on health monitoring

This chapter will describe the meaning and different approaches of health monitoring in general. The main components necessary for health monitoring are described in section E.1. The sensors and actuators are explained in section E.1. Section E.2 describes how faults are detected and why that is important for health monitoring. Section E.4 explains the different techniques for fault diagnosis. Section E.5 will describe the different approaches of health monitoring. Section E.6 describes the different maintenance strategies that are possible with the use of health monitoring. At last, section E.7 will summarize and conclude the findings of this chapter and answer the research question this chapter addresses: *"What are the existing approaches for performing health monitoring?"*.

E.1. Main components of health monitoring

According to Xu [55], health monitoring is a nondestructive technique that allows the integrity of systems or structures to be actively monitored during operation and/or throughout their lives to prevent failure and reduce maintenance costs. The monitoring part is done by a data acquisition system, which at least includes sensors, converters, and software. Sensors will convert a physical phenomena into a measurable electrical signal. A data acquisition device (DAQ device) will convert this analog signal to a digital signal, which the software of the computer can read. In some cases more equipment is required to gain readable and useful data. In the following subsections this will be explained per system.

Sensors used for health monitoring

Sensors are an important part in health monitoring as they convert physical phenomena into measurable electrical signals. There are lots of different types of sensors to be able to measure a variety of data. Examples of data that can be measured is: speed, torque, loads, pressure, vibration, sound, velocity, strain, rpm, acceleration, location, temperature, light, displacement, pH, and much more. Imagine all the different types of sensors that come along with this great variety. This subsection will describe the main sensors used for machinery at container terminals.

Sensors are used to check the state or health of components of machinery. Different sensors measure different parameters, such as temperature, speed, voltage, radiation, distance, etc. Measuring different parameters can be done with: temperature sensors, tachometers, accelerometers, thermocouples, strain gages, or even non-contact measurement systems like electromagnetic sensors, optical sensors, or capacitive sensors. Ultrasonic sensors are often used in structural health monitoring to identify the forming of cracks in large mechanical structures. Of course there are many more options for measuring data. The use of bar codes, QR codes, RFID technology, voice recognition, optical character recognition (OCR), magnetic strips, and switches for measuring specific parameters is possible as well.

Another option is the use of fiber optic sensors. Fiber optic sensors have the opportunity to measure many different structural parameters, while being immune to electromagnetic interference, and while being able to operate in high temperature environments. When a large amount of sensors is required but weight has to be limited, fiber optic sensors are perfect in the sense that a single fiber can contain thousands of sensors. This also makes it easier to install. Instead of multiple sensors with separate wiring per sensor, only one fiber has to be installed [55].

Data acquisition

Data acquisition is the process of measuring an electrical or physical phenomenon. This data can be used to monitor system performance, to evaluate the behavior of a product under certain condition, to test system behavior to optimize performance, and for much more. Data acquisition is done by a data acquisition system (DAQ system). In this case, a computer based DAQ system is described.

A computer based DAQ system requires sensors, DAQ devices and computer software. Computers cannot read the analog data that comes from the sensors, so a converter is necessary. A measurement device, also called a DAQ device, converts the analog output of sensors to digital input for the computer. A DAQ device might also be equipped with a signal conditioning system, when the signal first needs to be improved before it will be converted to a digital signal. The computer operates the DAQ device via specific driver software and manipulates the signal via application software. At this point the computer is able to check the condition of the machinery that is being observed by sensors.

Whenever the sensor output is too noisy or low-leveled (or in other ways difficult to read), signal conditioning will help improving the signal and get better quality measurements. This will help the DAQ device to correctly convert the analog data into digital data. Main types of signal conditioning are: amplification (when the signal is too small to read for the DAQ device), attenuation (when the signal exceeds the limits of the DAQ device: too large to read), filtering (to remove unwanted noise, or to block unwanted frequencies; lowpass filters), and isolation (without direct physical connection; optical, electromagnetic, capacitive). All types of signal conditioning have their benefits and disadvantages. Depending of the type of output signal, a signal conditioning method will be required. Linerization, bridge configuration, the use of relays, cold-junction compensation, and excitation types are also methods of signal conditioning.

Amplification has the benefit of increasing a signal when it is too small to read for the DAQ device, which is often the case with thermocouples. Amplification also maximizes the use of the range of the converter and it increases accuracy. But increasing the signal unfortunately also means that the noise in the signal will increase. Therefore it is important to put the amplifier as close to the source as possible.

Attenuation is the opposite of amplification and is used when the output signal is too large and exceeds the limits of the DAQ device. It is necessary for measuring high voltages that do not fit within the range of the DAQ device. The amplitude of the signal will be decreased.

Isolation will help to pass the signal from its source to the DAQ device without direct physical contact to either the source or the DAQ device. This protects your instrumentation and can be done in several ways, for example: electromagnetic, capacitive, and optical.

Data communication

After data acquisition, it is necessary to communicate this data. Data communication is possible between sensing devices themselves, but also between sensing devices and computer systems. Different configurations are possible. In this subsection the remote communication and its requirements are discussed.

A remote network - also known as a wireless network - consists of sensor nodes, gateways of routers, and a computer or server. A wireless connection makes it a remote network. A sensor node includes the sensor itself, the AD-converter and the DAQ device. These sensor nodes have a wireless connection with the router, which has a wireless connection to the computer or server. It is important to have a steady network and to prevent network failure. The strength of a network can be improved by choosing the right network topology. Figure E.1 shows the different arrangements of networks. The types star, tree, and mesh are also called a hybrid network, or a ZigBee network.

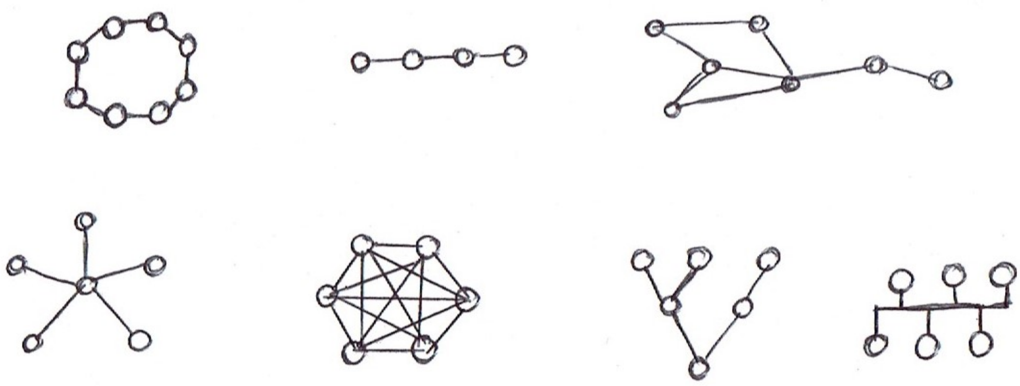

Figure E.1: Network topology, from left to right: ring, line, mesh, star, fully connected, tree, bus

Sometimes a loss of connection is inevitable. This can be caused by signal failure (for example by interference or blockage), or by the malfunctioning of one of the devices. In any of these cases it is imported the lost connection is fixed quickly. A self-healing network makes sure that even with a failing signal, the device that lost connection will automatically be re-connected to the network. This can be done by creating a new link and re-connecting with another device. The following figures will give a visual interpretation of a self-healing network.

RFID technology

An example of data communication is RFID technology. RFID stands for Radio Frequency IDentification and is a technology that is used to achieve the exchange of data by radio waves, to make data communication possible. For this to work, a receiver and a sender is required. With this technology it is possible to identify, track, and trace any object where the RFID tag or sender is attached to. A complete RFID system consists of the RFID tag with an antenna, an RFID reader with antenna, and an application (or software) on a computer.

RFID technology has many benefits relative to other visibility technologies. It supports real-time tracking and tracing of objects, while having better security and increasing throughput as big amounts can be red simultaneously. A disadvantage of RFID technology is that the RFID tag itself requires a battery, or - in the case of a passive tag - can only be in a small range (less than 10 meters) of the reader. Table E.1 shows the different classes of RFIDs.

class	Description	Functionality	Remarks
0	Read only	Passive tags	Data can be written only once (by manufacturer) and can be red many times
1	Write once, Read only	Passive tags	Data can be written only once (by user) and can be red many times
2	Read and write	Passive tags	User can read and write data many times
3	Read and write	Semi-passive tags	Can be coupled with on board sensors for capturing parameters
4	Read and write	Active tags	Can be coupled with on board sensors and act as a radio wave transmitter to communicate with the reader

Table E.1: RFID classification [20]

The class 2 RFID tags have a larger memory than class 0 and 1 tags. They also have the option for encryption and authenticated access control. Class 3 tags have a greater range of communication than class 0, 1, and 2 tags. Class 4 can communicate with other active tags and readers as they are capable of acting as a radio wave transmitter. Data logging is possible too.

Data analysis

After sensing the desired parameters with sensors, getting the correct data with data acquisition, and communicating the data with the computer or server, it is time to analyze the data and to take action if necessary. Taking action is required when - for example - one of the sensors detect failure in one of the components. The software must make a decision whether or not the machine keeps running or must stop to prevent more damage, it must decide how to cope with this failure. That is called decision making.

Different methods are used for decision making. Fault tree analysis, event tree analysis, decision trees, failure mode and effects analysis, Bayesian network, fuzzy technology and fuzzy sets, discrete event simulation, weighted PCA, Junction tree method, and many more methods are used for decision making. In the next chapter the found articles will be categorized also by their decision making methods (if possible). In table **??** these methods are shown.

E.2. Fault detection

With machinery and equipment it is important to know what state it is in. When a machine is running, it is desired that it works properly. With health monitoring it is possible to see what state the machine is in. This can be in good condition, but it is also possible that the machine is malfunctioning. To know if something is wrong, it is important to know how a machine can be malfunctioning. When the machine is not working properly, it is malfunctioning, which can be because of a fault or a failure. How that works, is explained in this section.

It is important to be able to detect faults in technical processes. Without it, faults will not be detected immediately and machinery could fail or break down. When one component malfunctions, it is possible to harm other components or machines in the rest of the chain. Early detection of faults could help avoiding more damage to other components or machines in the chain, increasing reliability and safety of the process [62].

Definitions

Before going in deeper, some basic terminology will be defined. Isermann defines the meanings of *fault, failure,* and *malfunction* in his book [53]:

> *"A **fault** is an unpermitted deviation of at least one characteristics property (feature) of the system from the acceptable, usual, standard condition."*

> *"A **failure** is a permanent interruption of a system's ability to perform a required function under specified operating conditions."*

> *"A **malfunction** is an intermittent irregularity in the fulfillment of a system's desired function."*

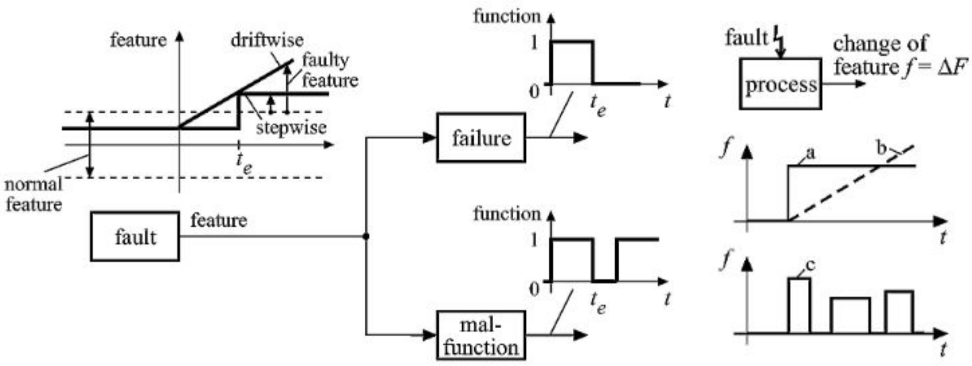

Figure E.2: Development of failure and malfunction [53] and the time dependency of faults: (a) abrupt, (b) incipient, (c) intermittent [53]

Faults can be caused by many different reasons. A fault can come from wear (or for example: corrosion), which machines and components will endure during operation. A fault can also be caused by wrong configuration, wrong assembly, or wrong installation.

There are different types of faults. There is the abrupt fault (which results in a stepwise signal change), the incipient fault (which results in a drift-like signal change), and the intermittent fault (where there are interruptions in the outgoing signal). See figure E.2 for a visual interpretation of the signal changes.

E.3. Fault detection methods

There are several methods to detect faults. Because there are many different technical processes, different methods will detect different faults. Fault detection methods can depend on many different aspects, which makes it necessary to have different methods for different processes. This subsection will explain more on the different fault detection methods.

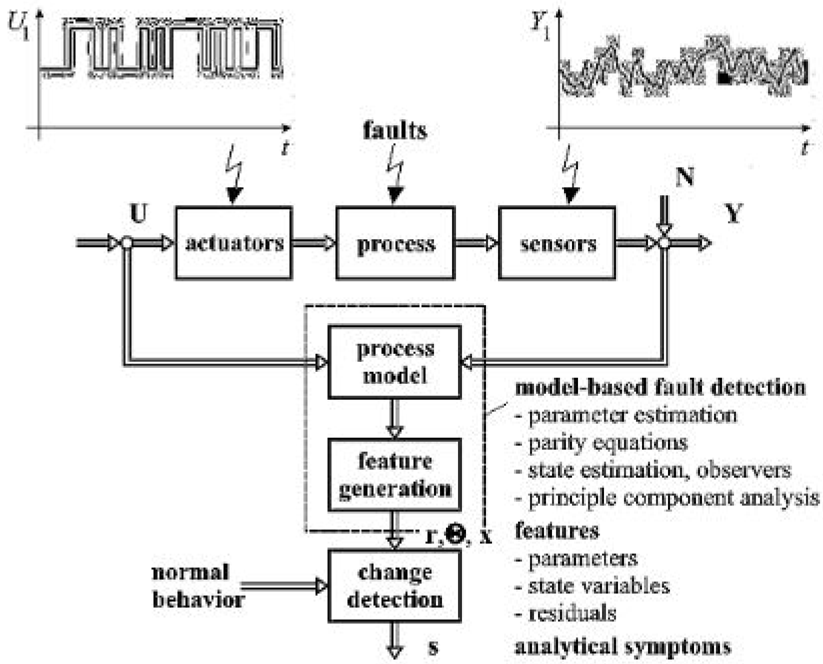

Figure E.3: Scheme for the fault detection with process models [53]

Process based fault detection

For model based fault detection it is required that the process can be described by a mathematical model. This method will use residuals to indicate changes between the model and the process. These residuals are changed significantly to make them appear larger and for a longer time, so that the model will be able to detect them. Depending on the complexity of the model and process, different methods may be applied [53]:

- Process-identification methods
- Parity equations
- State observers and state estimation
- Principal component analysis
- Parameter estimation

E.4. Fault diagnosis techniques

According to Isermann [53], figure E.4 shows a general scheme for fault detection and fault diagnosis. Fault diagnosis determines the type, size, location, and the time of detection of the most possible fault. As can be seen in figure E.4, the measured variables will be represented by analytical symptoms, and the observed variables will be represented by heuristic symptoms. Unified symptom representation makes it possible to diagnose the fault.

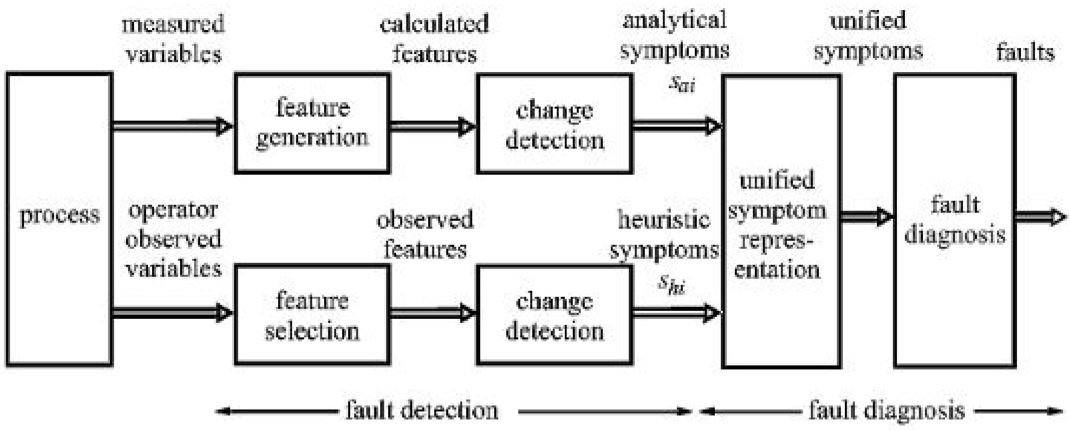

Figure E.4: General scheme for fault detection and fault diagnosis [53]

E.5. Approaches of health monitoring

Health monitoring contains checking, observing, tracking, testing, and supervising equipment. Different parameters can be measured and monitored: speed, torque, force, tension, vibration, power, position, temperature, sound, acceleration, and many more parameters. This section describes the most common types of monitoring, used in container terminals.

Xu describes health monitoring as follows [55]:

> *"**Health monitoring** is a nondestructive technique that allows the integrity of systems or structures to be actively monitored during operation and/ or throughout their lives to prevent failure and reduce maintenance costs."*

Isermann describes monitoring as follows [53]:

> *"Measurable variables are checked with regard to tolerances, and alarms are generated for the operator. After an alarm is triggered the operator then has to take appropriate counteractions."*

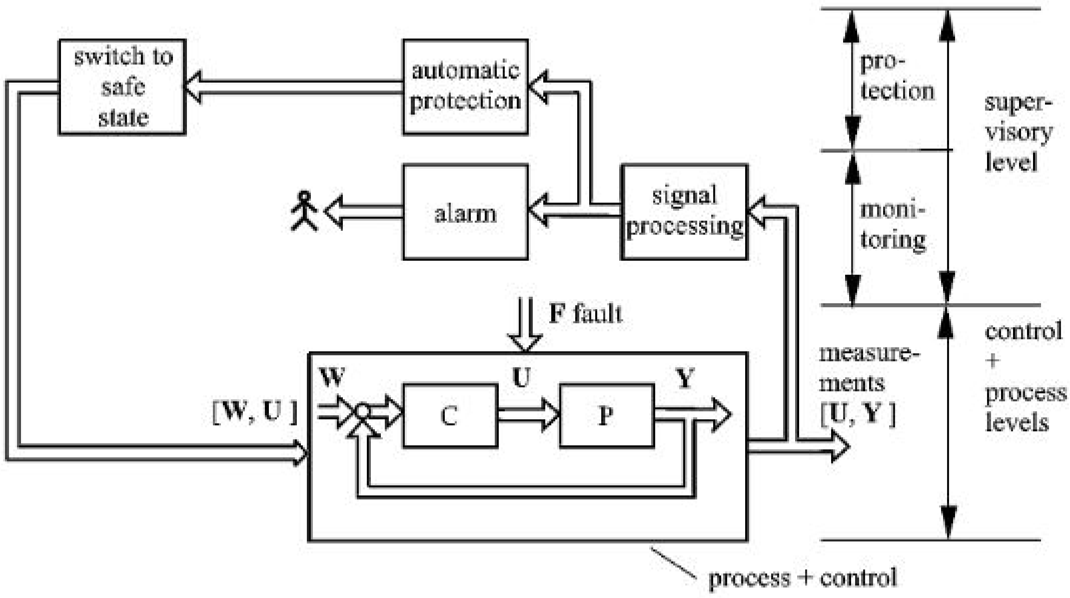

Figure E.5: Monitoring and automatic protection [53]

Operational monitoring

When critical data of equipment is collected at periodic intervals of time, it is called operational monitoring. Sensors measure critical characteristics of the equipment and this data is analyzed at a certain interval of time. For example: sensors could measure data after every ten seconds, or data could be collected after every minute. This saves a lot of computational power and storage compared to real-time condition monitoring, but it might just be too late to detect early stage of malfunctioning of the equipment that is being observed.

Structural health monitoring

Structural health monitoring is usually implemented in large mechanical structures to indicate the forming of cracks. D. Balageas [27]:

> *"Structural health monitoring aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although this can be altered by normal aging due to usage, by the action of the environment, and by accidental events. Thanks to the time-dimension of monitoring, which makes it possible to consider the full history database of the structure, and with the help of usage monitoring, it can also provide a prognosis (evolution of damage, residual life, etc)."*

D. Balageas describes the diagnosis in structural health monitoring as a new and improved way to make a non-destructive evaluation. The integration of sensors, smart materials, data transmission, computational power, and processing ability inside the structures make health monitoring possible [27].

Real-time condition monitoring

As the name suggests, real-time condition monitoring is monitoring equipment's condition in real time. The condition of an individual component is checked by sensors continuously in real time. With the use of (wireless) sensors, DAQ devices, data acquisition, data communication, and data analysis, it is possible to analyze real time data almost immediately. Real-time condition monitoring is mainly used for predictive maintenance and condition based maintenance.

Condition monitoring helps identifying faults and malfunctions in equipment in an early state. In this early state of failure, decisions must be made whether the component/ equipment continues its operation, or if a specific component needs to be replaced immediately. Making these decision based on condition monitoring is also called condition based maintenance, as the decision making mainly involves maintenance of the observed component. Real-time condition monitoring can also be the step to predictive maintenance, which will be explained in the next section.

Poza et al. [10] monitors the event channel instead of the nodes and uses a multi-agent architecture as a framework to optimize the complete yard management. An event-oriented channel is used to support the communication between agents. A set of adaptable, versatile, flexible, and robust applications is developed with the use of this multi-agent paradigm, with the goal to effectively manage the container terminal.

Pellegrino and Degano [22] use petri-nets to define a hierarchical monitoring structure for real-time fault diagnosis and recovery in an intermodal container terminal. A real case study is done for the terminal in the port of Genova, Italy. The monitoring and control architecture they came up with, is shown in figure E.6.

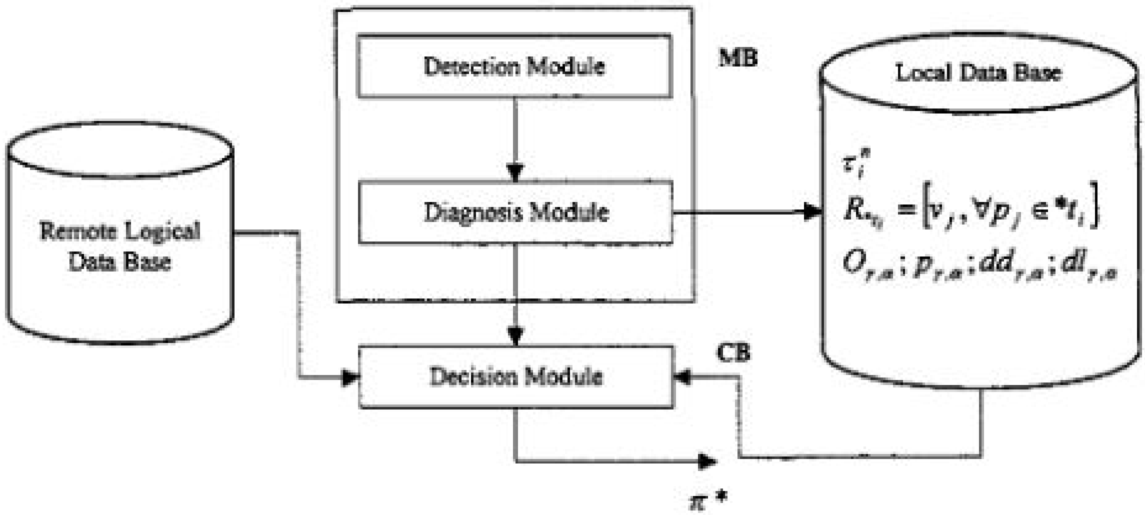

Figure E.6: The monitoring and control architecture for the intermodal container terminal in the port of Genova, Italy [22]

Yang et al. [13] describe the main requirements and guidelines for container terminals as well as the challenges related to calibration and testing of distributed sensing systems of the main equipment of container terminals (quay cranes, AGVs, and yard cranes). Their conclusion is that remote sensing technologies (RFID, cameras, and computer vision algorithms) may contribute to safer and reduced time handling operations. This paper also discusses structural health monitoring for quay cranes (see figure **??** in the next section) and different communication solutions (see figure E.7).

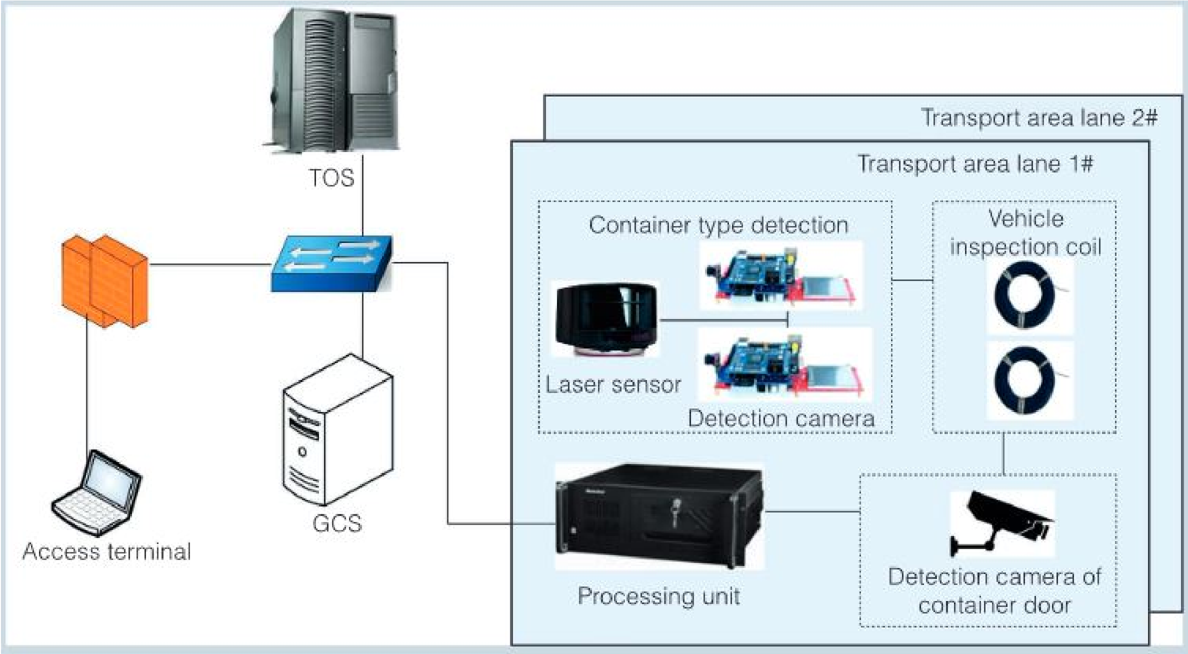

Figure E.7: Distributed container identification system [13]

Fornara, Degano, and Febbraro [23] [21] use a discrete event system to describe an intermodal container terminal, because of the unforeseeable events resulting in delays from the a-priori planned schedule. A diagnosis procedure is triggured at the moment an irregulation that could indicate a failure or malfunction is detected. The paper defines a hierarchical monitoring structure with the use of petri nets intended to real-time fault diagnosis and recovery. The petri net model helped describing the synchronization problems and behaviour of the terminal. The model can regulate the scheduled planning and detect its delays and deviations. The petri net model helps with the proposed hierarchical architecture for fault monitoring. A difference is made between transient (can be regulated by a local controller) and permanent (requires intervention of the central regulator to let the local controllers co-operate) delays.

Kocielski [56] investigates excisting maintenance models and wonders it they are applicable to container terminals. Global solutions and consideration of the individual needs and local circumstances of a terminal are combined to investigate these maintenance theories for container terminals. Kocielski also creates a diagram with different maintenance models, as can be seen in figure E.8. Their conclusion is as follows: *"The models implementation reveals its practical validity, but in fact maintenance deals with highly diverse problems even in firms within the same productive sector, due to this is very difficult to design an operating methodology of general applicability"*.

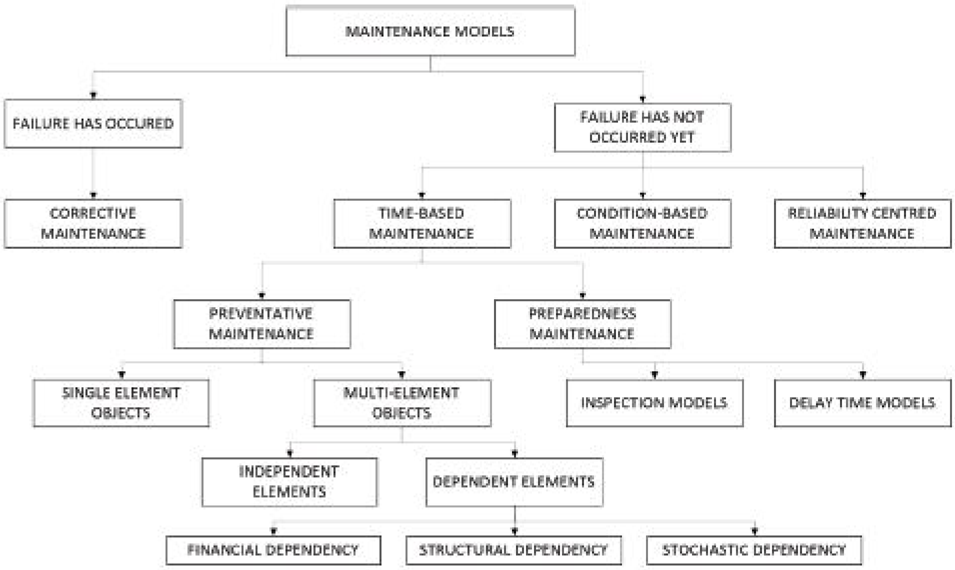

Figure E.8: Maintenance models classified [56]

Wang et al. [74] describes the importance of informatization in China's western port, since it is still at a low level. It describes the technological development and evolution of other container terminals around the world, to analyze their differences, and research their problems. The need for development of an integrated system including remote wireless monitoring and intelligent management to make condition monitoring possible is described, as well as the steps (intellectualization, automation, and integration) that have to be taken.

E.6. Maintenance strategies

There are several types of maintenance. Since this literature report focuses on health monitoring instead of maintenance, only the most common types of maintenance (in automated container terminals) will be briefly described in this section [55] [34] [63].

Isermann [53] states that:

> *"Maintenance is understood as an action taken to retain a system in, or return a system to its designed operating condition. It extends the useful life of systems, ensures the optimum availability of installed equipment or equipment for emergency use."*

and:

> *"Maintainability is a quality of several features which enable a system to be maintained. This includes proper design, required tools, standardized components, group subsystems (modularity), aids for trouble-shooting, space parts and logistics. The downtime is the interval where the system is not in acceptable operation and can be separated in diagnostic time, active repair time, logistic time and administrative time."*

Corrective maintenance

Corrective maintenance is also known as run-to-failure maintenance. This means that the machine keeps operating until it fails. Once it fails or once it has stopped working because of a failure, the machine will be checked on failures. There is no schedule for maintenance in this case, the maintenance is emergency based. The maintenance is not done only until a malfunction appears. This malfunction may cause a shutdown of the system, resulting in a large downtime and most often resulting in high costs as well.

Random maintenance

Random maintenance is opportunity based. This could be when a machine malfunctions, but does not have to be just when it malfunctions. Random maintenance is done when the opportunity arises. This can also be triggered by the condition of a component. It is also possible that one of the machines fail and that the other machines are checked in the meantime, because the entire process is shut down because of the first fail. Once it turns out it is better to perform maintenance on other parts as well, it might as well be done in the same downtime.

There are more reasons for random maintenance. A power failure might occur. And instead of waiting for the power to return, it is also possible to check the machinery in the meantime and perform maintenance if necessary. It is not necessary for random maintenance to be only done after a malfunction appears.

Preventive maintenance

Preventive maintenance is maintenance that is scheduled at certain time intervals to prevent breakdown or malfunctioning of equipment. The interval may be based on previously observed degradation of components. An example of preventive maintenance is the periodic oil change in the crane's gearbox after a specific amount of running hours.

Predictive maintenance

Predictive maintenance is condition based. Parameters of components are measured constantly and when an irregularity occurs, maintenance will be scheduled. Predictive maintenance is a lot like preventive maintenance, but with constant monitoring of components.

Predictive maintenance is scheduled, like preventive maintenance, but it is not scheduled on forehand for every amount of running hours or running cycles, which is the case for preventive maintenance. The sensors collect data and based on that data the software will decide whether or not the machinery is in a good working state or that it requires maintenance. In that last case, the software must decide when the maintenance should be done. The sensors can pick up a slight irregularity and decide to keep the machinery running when it is not in an emerging state. The software will schedule the maintenance for later.

E.7. Conclusion

with health monitoring it is possible to check the state of equipment and machinery. It makes it possible to analyze data of machinery, which might be invisible for humans. With sensors it is possible to detect failures faster than with only human operators. Health monitoring knows different approaches with different maintenance strategies.

Structural health monitoring is used to identify cracks in large structures. This is important for the large quay cranes. Collecting this type of data helps with indicating the formation of cracks in the future as well, preventing accidents from happening.

Operational monitoring collects and analyzes critical data of equipment at periodic intervals of time. This is done to save computational power and to save storage space, which is a huge advantage. The biggest disadvantage is that malfunctions might be detected too late and that the damage is already done, but could have been prevented by a smaller interval or with real-time conditioning.

Real-time condition monitoring will check the condition the machinery is in in real time. A lot of sensors and data acquisition is required for this. This health monitoring approach is mostly used for predictive maintenance and condition based maintenance.

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Afterword

As part of the coal phase-out, it is forbidden from the year 2030 to use coal for energy production in power plants in The Netherlands. Some countries have already stopped using coal in power plants, while other countries are still planning the coal stop [70].

Nevertheless, this thesis proposed a maintenance strategy that works well for today's industry. The methodology behind the strategy - Failure Modes, Effects, and Criticality Analysis (FMECA) - is a flexible and adjustable systematic method which can be used in other industries as well. This thesis proposes a solution to reduce downtime and maintenance cost, while increasing reliability and safety. This thesis might focus on conveyor belt systems in a dry bulk terminal, however it is possible to adjust the strategy to conveyor belt systems in an airport, for example. Conveyor belt systems will always be around in some way.

Hopefully, this maintenance strategy will have a place in EMO's company in one way or another. This proposal uses the already existing condition monitoring data and will help making maintenance more efficient by decreasing downtime and maintenance cost. Even though dry bulk terminals might not be around forever, it is better to keep operation as reliable and safe as possible while they still exist. Maintenance cost and unplanned downtime must be kept as low as possible. EMO B.V. can benefit from this strategy and keep being one of Europe's largest and most innovative dry bulk terminals.

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K. S. de Vos
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